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WOODBRIDGE SCHOOL ESSAYS

NUMBER I

THEORETICAL ASTRONOMY

DYNAMICS OF THE SUN

BY

J. WOODBRIDGE DAVIS

NEW YORK
D. VAN NOSTRAND COMPANY
23 MURRAY AND 27 WARREN STREETS
M DCCC XCI

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of
J Woodbridge Davis
645 Mad. Ave.

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GILLISS BROTHERS
400 & 402 WEST 14TH STREET
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To the Astronomers

this suggestion is offered with the profound respect of its author.

ERRATA

Page 10, in condition **C**, $[f''(\tau) > f'''(\tau)]$ should read $[f''(\tau) < f'''(\tau)]$.

Page 21, in formula (13), $\frac{D}{D}$ should read $\frac{D}{D_0}$.

Page 21, in formula (16), $\frac{D_0}{p^{\frac{1}{\kappa}}}$ should read $\frac{D_0}{p_0^{\frac{1}{\kappa}}}$.

Page 29, in formula (50), $\frac{v_0}{v}\frac{r}{r^2}$ should read $\frac{v_0 r_0^2}{v r^2}$.

Page 30, in formula (54), f_{iv} should read f^{iv}.

Page 31, in formula (55), Q_1 should read Q'_1.

Page 75, in twelfth line, "was" should read *were*.

ORDER OF TOPICS

MATTER — GRAVITY — HEAT

CONSIDER a body in ethereal space, so far removed from extraneous forces that the effects of these are insignificant upon that body.

It consists of some mixture of solids, liquids and vapors,* † and contains some quantity of heat.‡

The solid and liquid portions fall together and form a nucleus. This retains the original energy of rotation of its constituent particles. The vapors range themselves about the nucleus.

In its state of isolation, the body obeys without interference the impulses of its own inherent forces, and, therefore, acquires a spheroidal symmetry in shape, density, temperature, pressure, rigidity, and all other circumstances.

The behavior of the atmosphere depends upon the mass, density and temperature of the nucleus.§ For abbreviating the discussion we shall find the following symbols convenient.

r — the distance from centre to any concentric stratum of atmosphere.

V — the volume of vapor bounded by this stratum and the surface of nucleus.

m — the mass of vapor bounded by this stratum and the surface of nucleus.

D — the density of this stratum.

p — the pressure at this stratum per unit surface.

* This includes the cases wherein any one or two of the constituents are absent; so, the proposition is universal.

† The term *vapors* is used to denote all the gases.

‡ Kinetic and potential.

§ If the body consist of gas only, the portion contained within any concentric sphere can be considered to be the nucleus with respect to the outlying portions.

τ — the absolute temperature of this stratum in centigrade degrees.
v — the velocity of a particle of this stratum.
g — the acceleration due to gravity at this stratum.
t — the time required for a particle to flow from the surface of nucleus to this stratum.
r_0 — the mean radius of the nucleus. This corresponds to $t = o$. The corresponding values of the other variables are also denominated by the subscript zero.
m_1 — the mass of the nucleus.
m' — the quantity of matter vaporized per second.
Q — the quantity of thermal energy expended at any time.
Q' — the quantity of heat expended in a unit of time.
Q'_1 — the quantity of heat expended in a unit of time upon a unit of surface of the nucleus.
I — the quantity of thermal energy expended in molecular or atomic work.
δ — the relative density of any vapor in comparison with hydrogen.
x, κ — the quotient obtained by dividing the specific heat of a gas at constant pressure by its specific heat at constant volume : $x = 1.408$.

Let the body consist of only one kind of matter.

Whatever the variations of temperature and pressure may be,

$$\tau = f(r), \qquad p = f'(r), \tag{1}$$
$$p = f''(\tau). \tag{2}$$

The relation between the maximum vapor-pressure and the corresponding temperature, is

$$p = f'''(\tau). \tag{3}$$

Now, the actual pressure between atmosphere and nucleus must be either greater than, equal to, or less than, the maximum vapor-pressure corresponding to the temperature of the nucleus ; that is,

$$f''(\tau_0) > f'''(\tau_0), \tag{4}$$

or,
$$f''(\tau_0) = f'''(\tau_0), \tag{5}$$

or,
$$f''(\tau_0) < f'''(\tau_0). \tag{6}$$

Let us discuss the conditions represented in formula (4). The vapor condenses; the temperature rises; v, t, m', Q', I are negative; m, and g_o increase: the intensity of gravity is preponderant over the intensity of heat.

Not only at the nucleus, but throughout the immediate region where the pressure, (2), exceeds the pressure, (3), does condensation occur. The limit of this region is determined by the equation,

$$f''(\tau) = f'''(\tau). \qquad (7)$$

That these functions must meet is evident. For, if the actual pressure, from the nucleus to infinity, were everywhere greater than the maximum pressure of vaporization, condensation would occur simultaneously through all this space, and would instantly reduce the function (2) to the function (3).

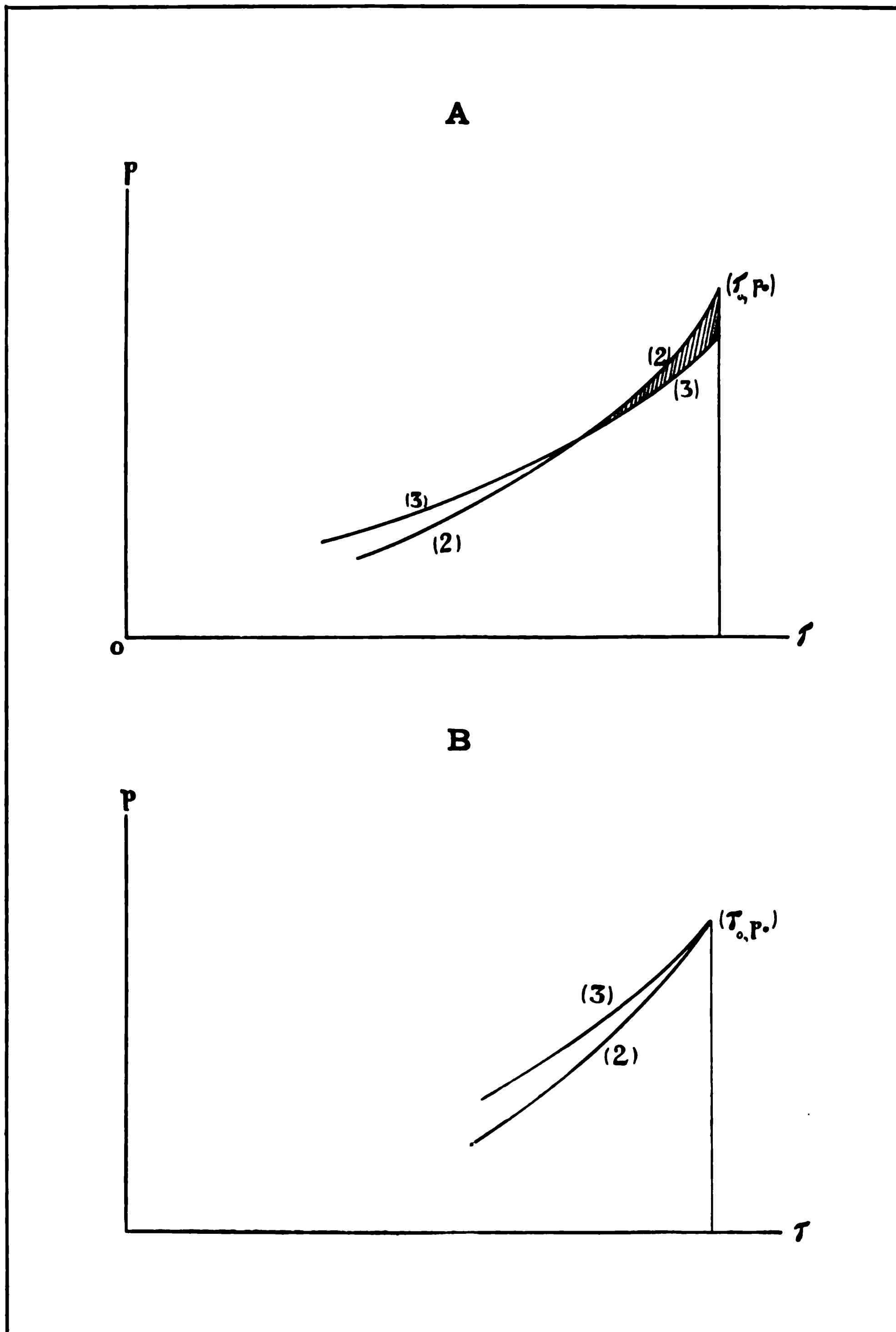
But, whether junction is effected, or intersection, a dynamical equilibrium is established, which is progressive in its character. Vapor and mist descend upon the nucleus, which grows in matter and in heat. The heat and, if incandescent, the light, are hindered from escaping by the enclosing vapors, which are cooler on the outskirts than within. The external aspect is of a misty body of indefinite outline. If sufficient heat is contained to produce incandescence, the nebula is illumined with a diffused dull red light.

Let us discuss the conditions represented in formula (5). Vapor is neither generated nor condensed; the temperature is unchanging, the mass unchanged, the atmosphere motionless, or tending to become so. Heat and gravity are balanced. A perfect statical equilibrium exists.

Function (2) can never exceed function (3) in value. Otherwise, condensation would occur above the nucleus, and evaporation at its surface, and the equilibrium indicated in formula (5) would be destroyed. Therefore,

$$f''(\tau) \leqq f'''(\tau). \qquad (8)$$

The external aspect is of a well-defined, unobscured liquid or solid body, cool or incandescent.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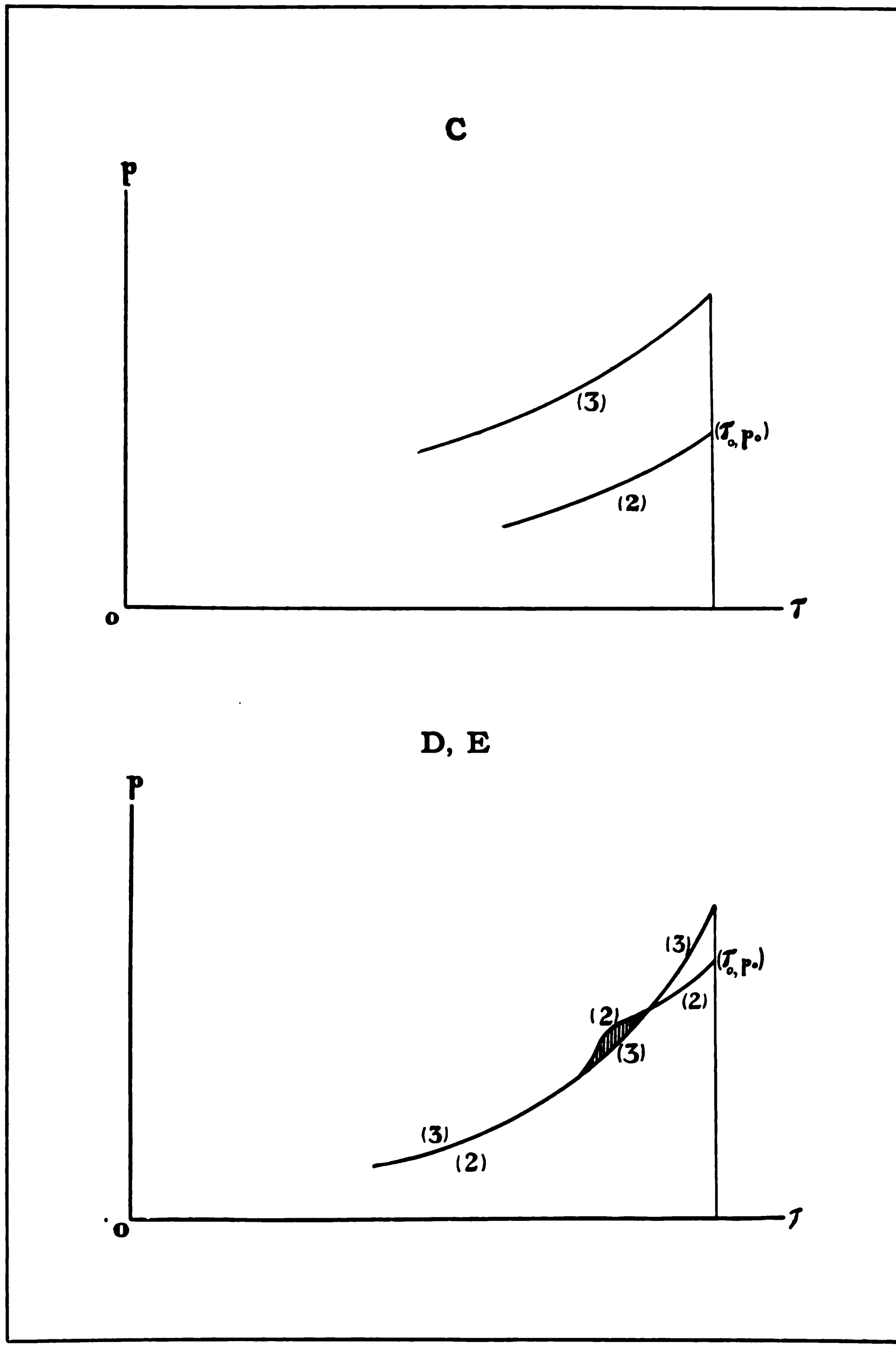
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It remains to discuss formula (6). If functions (2) and (3) do not intersect, vapor is continually generated, and driven off as a limpid atmosphere; the temperature falls; v, t, m', Q', I, are positive; $m_{\prime}$ and g_0 decrease; a dynamical equilibrium exists, progressive in its character. Heat preponderates over gravity. The aspect is the same as in the case of statical equilibrium.

If the functions, (2), (3), do intersect, vapor is still continually generated at the nucleus, rising as a limpid atmosphere to the region that begins where equation (7) is true, and there partially condensing. Beyond the region of condensation the vapor extends indefinitely, carrying to a greater or less distance the particles of condensation. So far as this dust accompanies the vapor, so far must function (2) coincide with function (3). If the nucleus be incandescent, the first layers of the cloud may be incandescent too.

The vapor is delivered to the region of condensation with a certain velocity. The motion of the vaporous remainder continues to be accelerated on account of its resident elastic force. Because the condensed particles are thoroughly enmeshed in the gas, they, too, continue to be accelerated outwardly. But gravity imparts an opposite acceleration. Accordingly as one or the other of these is more potent, the matter ejected from the nucleus forever flies away, or the liquid and solid portions return. Whether the velocity and subsequent acceleration are sufficient to drive the comminuted particles to a small distance from the nucleus, or to a vast distance, or to an infinite distance, or are more than sufficient this to do, depends simply upon the relation between the intensity of heat and the intensity of gravity. In the one case a dynamical equilibrium, cyclical in its character, so far as the condensed particles are concerned, is established; in the other a dynamical equilibrium, progressive as regards both gas and dust. In either case some matter and some heat are lost.

The external aspect is not that of a body wrapped in impenetrable gloomy mist; but, when the intensity of heat is little paramount, that is, when

$$f'''(\tau_0) - f''(\tau_0) \tag{9}$$

is small, the apparition is that of a cloud-girdled sphere through the rents in whose mantle appears the dark body of the orb. The bright clouds seem to float in the limpid air; in reality, they but mark the region wherein the flying vapor becomes visible by partial condensation. The inferior margin is sharply defined, the superior is more indefinite.

Corresponding to a larger value of function (9), the cloudy stratum is thicker and further removed, the rifts fewer, the nucleus seldom or never seen.

If the nucleus be highly incandescent, and the value of function (9) small, the cloud stratum is either not incandescent or but faintly luminous, because the supply of materials is slow and the region is drenched by the cold descending mist of outer spaces. But, if the value of function (9) be very great, the light emitted by the stratum of condensation is vivid, because the gas is then delivered in vast quantity at high temperature, and the cold materials are borne away by the blast. According to the powers of illumination and obscuration possessed by the cloud stratum, the nucleus is, or is not, seen.

Let us arrange more compactly the account of the circumstances of these various cases.

A. DYNAMICAL EQUILIBRIUM—PROGRESSIVE.

Vapor and mist descending.

Heat < Gravity.

$f''(\tau_0) > f'''(\tau_0)$

$\left[f''(\tau) > f'''(\tau)\right]_0^a$; Condensation.*

$\left[f''(\tau) < f'''(\tau)\right]_a^\infty$; Limpidity.

τ_0, m_1, g_0, increase.

t, v, m', Q', I, are negative.

Aspect: A misty body of indefinite outline, which may shine with a diffused dull light.

* Limits are in values of time for conditions *A*, *C*, *D*, *E*; in values of distance for *B*.

B. STATICAL EQUILIBRIUM.

Vapor quiescent; no mist.

Heat = Gravity.

$f''(\tau_0) = f'''(\tau_0)$

$\left[f''(\tau) \lesseqgtr f'''(\tau)\right]^{\tau=\infty}_{\tau=0}$; Limpidity.

τ_0, m_1, g_0, are constant.

t, v, m', Q', I, are zero.

Aspect: A well-defined, unobscured, liquid or solid body, cool or incandescent.

C. DYNAMICAL EQUILIBRIUM—PROGRESSIVE.

Vapor ascending; no mist.

Heat > Gravity.

$f''(\tau_0) < f'''(\tau_0)$

$\left[f''(\tau) > f'''(\tau)\right]^{\infty}_{0}$; Limpidity.

τ_0, m_n g_0, decrease.

t, v, m', Q', I, are positive.

Aspect: A well-defined, unobscured, liquid or solid body, cool or incandescent.

D. DYNAMICAL EQUILIBRIUM—

Progressive for vapor, cyclical for mist.

Vapor ascending; mist ascending and descending.

Heat > Gravity by little.

$f''(\tau_0) < f'''(\tau_0)$

$\left[f''(\tau) < f'''(\tau)\right]_o^a$; $\left\{\begin{array}{l}\text{Rising Vapor,}\\ \text{Falling Mist.}\end{array}\right.$

$\left[f''(\tau) > f'''(\tau)\right]_a^b$; Condensation.

$\left[f''(\tau) = f'''(\tau)\right]_b^c$; Vapor and Dust.

$\left[f''(\tau) \leqq f'''(\tau)\right]_c^\infty$; Limpidity.

τ_o, $m_{\prime\prime}$, g_o, decrease.

t, m', Q', I, are positive.

v is positive for gas, positive and negative for mist.

Aspect: If cool, as a cloud-girdled sphere, the clouds floating upon a limpid atmosphere; if incandescent, the clouds may be faintly luminous.

E. DYNAMICAL EQUILIBRIUM—PROGRESSIVE.

Vapor and mist ascending.

Heat > Gravity by much.

$f''(\tau_o) < f'''(\tau_o)$

$\left[f''(\tau) < f'''(\tau)\right]_o^a$; Limpidity.

$\left[f''(\tau) > f'''(\tau)\right]_a^b$; Condensation.

$\left[f''(\tau) = f'''(\tau)\right]_b^\infty$; Vapor and Dust.

τ_o, $m_{\prime\prime}$, g_o, decrease.

t, v, m', Q', I, are positive.

Aspect: If cool, as a sphere of bright clouds concealing the nucleus; if incandescent, as a sphere of condensed vapor emitting a vivid light, entirely or partially obscuring the nucleus, and surrounded by a sub-incandescent stratum of vapor and dust exhibiting signs of rapid outward motion.

As the temperature changes, the circumstances and aspect change also. If the change be adiabatic, and the body in condition **A**, the characteristics of that condition gradually diminish and disappear, leaving the body in the state **B**. If radiation, which increases as the change progresses, be considered, the body reaches the state **B** after a longer interval of time. If the body be in condition **C**, the characteristics of this condition diminish until the substance has been entirely converted into gas, or until state **B** is reached. If radiation be considered, this state is sooner reached, and then the body passes to condition **A**, in a moderate degree of activity. Likewise state **E** subsides through **D** to the condition of statical equilibrium **B**, surpassing this, if radiation be considered, to an imperceptible manifestation of **A**.

If not only the loss of heat by radiation be regarded, but, also, a gain from foreign source by some means that little affects the atmosphere, as by the implunging of solid masses; then, the changes may begin at any state and proceed in either direction. With a greater gain than loss, the manifestations of state **A** decline; the atmosphere clarifies and becomes still; next it rises, limpid for a little space, beyond that, misty, the aspect of the body clothed with this appearing mist being like that possessed while it was still clothed with the disappearing mist of condition **A**. But, as the temperature waxes, the characteristic aspect of states **D** and **E** becomes quite distinct from that of state **A** when it, also, is in intense activity. The mist no longer fills the denser portion of the atmosphere, from the very nucleus outward, presenting an indefinite outline, and an impenetrable depth, but occupies the higher, rarer regions, where the depths are penetrable down to the stratum of densest cloud first formed, which, being impenetrable, presents a boundary fairly well defined.

As the temperature yet rises, the cloudy stratum upward moves, this motion being not of particles, but of a region. If incandescent, the intensity of heat and light increases as the visible disc grows larger.

If it be possible that condition **C** can for the substance exist, and continually so, then the increments of temperature simply add to the brilliancy of the nucleus and the intensity of its calorific and actinic rays, leaving it unobscured.

The cloud-producing potency of the vapor at any place is indicated by the positive values of the function,

$$f''(\tau) - f'''(\tau), \qquad (10)$$

and the cloud-dissipating power by the negative values.

The second term is a constant function for any substance; the first is a variable function. While statical equilibrium exists, the difference of pressures at any two strata is simply the weight of the included gas: while condition **A** exists, the difference of pressure for the limpid portion is equal to the weight of the included gas diminished by the acceleration of its velocity: while conditions **C**, **D** or **E** exist, the difference of pressure, in the region of limpidity, is the weight of the same portion of vapor increased by the acceleration of its velocity. In the regions of condensation and of rising and of falling mist, functions (1) and (2) change, the latter inclining toward function (3). There is a further change due to the resistance the gas meets in passing the particles of deposition.

We have treated of a single kind of matter and have obtained definite results: let us consider a body composed of many kinds of matter.

If the nucleus is liquid, or has been so, the heavier substances are mainly descended to the centre and preserved from vaporization; though portions of these may be held in the surface regions by chemical combination: so the vapors are principally composed of lighter substances.

There is now to be considered not only simple vaporization and condensation, but chemical composition and decomposition, which is governed in the same way by the relation between pressure and heat. In general, pressure opposes and heat favors the evolution of gas whether from an elemental liquid state, or from a compound, by laws that are expressed by entirely similar functions. Furthermore, recombination takes place, after the manner of condensation, as the temperature falls, with the production of heat, which may be more intense than that which caused the dissolution. It will be convenient, therefore, to let the word *condensation* include both molecular and atomic condensation; and to extend the sig-

nification of the term *vaporization* to include the evolution of gases from denser compounds.

The atmosphere consists of the vapors of substances residing at the nucleus.* All possess the same temperature ; each its own pressure. The tendency for each vapor is to assume one of the states of statical or dynamical equilibrium already discussed. But, because the gases are thoroughly immixed, the motion of each is dominated by the motion of all, and this is determined by the tendency of the greater mass of the vapors.

If the temperature be so low in comparison with the acceleration due to gravity that the majority of the gases are inclined to fall, the atmosphere in general descends, bearing down upon the vapors of the more volatile substances, and causing their pressures to be increased ; so that, upon the whole, condensation occurs, and the vaporization even of the volatile substances is retarded. Condition **A** exists, functions (2) and (3) becoming means for the congregation of gases ; but the limit of the region of condensation extends beyond the limit for the mean vapor.

* It is tacitly assumed throughout these discussions that every substance at every temperature of the absolute scale is accompanied by its vapor, or the vapors of its elements. When the physicist announces that he cannot detect the pressure of aqueous vapor at a temperature below —40° of the centigrade, or Fahrenheit scale, he simply states that his apparatus is not sufficiently delicate to indicate the diminished pressure. It is unlikely that the gas suddenly collapses into dust at a certain point : the presumption is that the diminution of pressure is continuous, as he finds it throughout the range of his experiments. If two instruments known to be of different degrees of delicacy agree in failing to indicate pressure at the same point of temperature, the presumption must be that the vapor there collapses ; if they do not thus agree, the presumption must be that the variation of pressure is continuous beyond the range of either. Very delicate means that are as yet not quantitative, indicate the presence of vapors at pressures very far below the intensity that can be indicated by the most sensitive manometers. Among such are the sense of smell, and, also, the rational faculty that makes known the existence of the ethereal medium. The wonderful tenuity of the vapor rising from a particle of musk has often been commented upon.

According to this assumption, it is considered, for instance, that the earth's atmosphere contains traces of every substance exposed at its surface, although the ordinary quantitative analyses show but few of them. The lowest stratum is filled with the odors of animal, vegetal and mineral substances—the smells of soils and seas ; and, when the electric flash pierces the altitudes of air, the spectroscope reveals the presence of many familiar elements. Conclusions from the latter phenomenon are, however, rendered uncertain by the fact that the incandescent vapors may be sprung from meteoric dust.

While the foregoing assumption, as being more probable, is tacitly made throughout these discussions, it is by no means essential to the development of the theory. Even though some substances could never be vaporized, and all others not below, for each, a certain temperature, the deductions to be made from the theory of the mutual effects upon matter of its own gravity and heat, remain essentially the same.

At a certain higher temperature, the total tendency to fall is balanced by the sum of the tendencies to rise. There is no general descent of the atmosphere; yet the heavier gases continue to settle down and liquefy, and up through these still struggle the more volatile vapors. All the conditions from **A** to **E** are together blended, but all the opposing motions are retarded. The atmosphere is not clear, but presents the aspect **A**.

When heat is somewhat predominant over gravity, the quantity of matter vaporized is more than that condensed. The atmosphere in general ascends. If the motion be sluggish, the heavier vapors still filter through and as sluggishly descend. The condition and aspect are those denominated **D**, wherein the functions, (2), (3), are means; but the limits of the region of condensation extend both ways beyond the limits for the mean vapor.

At a very high temperature condition and aspect **E** exist, even though a few gases might still incline to fall, for such are blown away. But the cloudy stratum is broadened, or several such strata separately shine, on account of the difference in value of function (10) for the various components of the atmosphere.

It is to be remarked that at the extremes, where gravity predominates vastly over heat and where heat predominates vastly over gravity, the unison of tendencies causes the conditions and aspects **A** and **E** to be essentially the same as for a single substance, while in the vicinity of the statical condition, **B**, the conditions and aspects are rendered ambiguous by the conflicting tendencies of a multitude of vapors, the appearance remaining constant through a certain range extending into conditions **A** and **D**. It has already been noted, however, that the appearance of the atmosphere of a single substance is the same in the contiguous portions of **A** and **D**. Consequently the intermediary condition is simply to be distinguished by the meagre manifestation of the typical aspect **A**.

The history of an isolated body, so far as its general motions and the variations of the intensities of heat and gravity are concerned, would seem to be as follows: In the primeval condensation the descending atmos-

phere includes the heavier and the lighter vapors. The former most readily liquefy; but, if the initial temperature be near the absolute zero, even hydrogen liquefies also. As the temperature becomes greater, the more volatile substances refuse to depart from the gaseous state, although the urging of gravity and the impressment of the other vapors have likewise increased. As the change progresses, these volatiles tend to relinquish the denser states and return to the atmosphere in a rising stream. At a later stage the temperature and pressure have reached such intensities that the chemical affinities between the volatiles and the non-volatiles are allowed to act. One after another the volatiles commence to be absorbed again by the nucleus. As the temperature still rises, both molecular and atomic condensations are resisted, and then for each substance in succession the tendency is toward the reverse transformation. It is when the sum of these tendencies becomes zero, although the separate actions of the gases are not entirely obliterated, that condensation as a whole ceases, and the first period of the history comes to a close.

The balance is not fixed. For, as the heavier gases continue to sink into the nucleus, developing heat, the lighter gases issue in greater volumes. The atmosphere begins to ascend, as its nature changes. Meanwhile, independently of the gaseous atmosphere, the temperature of the nucleus is increased,—by the impact of solid fragments of the body, falling in curved projectories toward its central mass, and also by the contraction of the nucleus itself, as it is more or less compressible in constitution. Thus, simultaneously, the intensity of heat in the nucleus grows, and the intensity of gravity in the atmosphere diminishes. The preponderance has passed to the other scale. When condition D is well entered upon, the ascending atmosphere contains but traces, or nothing, of the heavier gases, whose substances have been slowly sinking to the centre of the ball. On the other hand, the most volatile substances, or those most easily freed from atomic bondage, first rise as the main constituents of the atmosphere. At some distance they condense or recombine. With the waxing of the temperature, the region of condensation moves outward from the nucleus, as is observed in the atmosphere of comets; but this motion of the cloudy stratum in no wise marks the velocity of the vapor or of the cloud-cor-

puscles. Then, the next less volatile vapor becomes sufficiently abundant to condense in an appreciable cloud. So an inner stratum of cloud is formed,—for the less volatile sooner condense,—and this also moves outward with the growing of the nucleus' heat. Thus in succession the atmosphere becomes impregnated with less and still less volatile vapors, each condensing in its own stratum, distinct or merging with others, and each stratum moving from the nucleus with the growing heat—a phenomenon frequently observed in comets' atmospheres as they approach the sun. At last, whether condition **E** be reached or not, the expenditure of heat in producing motion becomes equal to the heat engendered in the nucleus; the temperature of the nucleus and the motion of the atmosphere have attained their maxima, and the close of the second period is at hand.

After this, the expenditure exceeds the generation: very gradually the outflying velocity of the atmosphere diminishes; very gradually the cloud strata retreat toward the nucleus. At length the intensity of heat can resist gravity only; the general motion of the atmosphere ceases, and the third period comes to an end.

As the nucleus continues to cool by radiation of heat to the outer regions of its atmosphere, the encompassing vapors again descend, not as at first, but slowly and imperceptibly. The least volatile condense. The most volatile also recombine with other elements until the temperature is so reduced that chemical affinity becomes inactive. Between this temperature and the exceedingly low temperature at which they will condense to elemental liquids, these most volatile of gases become the fixed atmosphere of the body, as the nitrogen and oxygen are of the earth's, and the substances of intermediate volatility still execute their changes as vapors, clouds and liquid surface films. The general condensation proceeds until the temperature has become uniform throughout the nucleus and atmosphere. The latter is then composed of the vapors of all the substances that remain upon the surface of the nucleus, besides the gases that are still removed from their points of condensation. At last perfect rest is reached: all motion ceases as the fourth period comes to its close.

If, instead of treating the body as isolated, we consider that heat

is radiated to foreign bodies, and that heat is received through the medium of extraneous falling solids, and by direct radiation from without, as in the case of comets traveling near the sun, the same cycle of changes is passed through, although the durations of the various periods are thus affected.

When we survey the solar system, we find that none of its bodies presents the aspect **A**, except comets at a considerable distance from the sun. But these, as they approach that grand centre, so soon exhibit the aspects **D** or **E**, that their first and final appearances of any cycle are undoubtedly that of the nebula whose atmosphere has no general motion. They mark the incipiency of the second period and the termination of the third. We need not, then, to discuss the falling atmosphere of the first period, in order to determine the present conditions of any body of our system; such discussion relates to the past history of these orbs, and is beyond the purpose of this essay.

Many of the comets, as they descend to perihelia, and then retreat to outer space, display in quick succession the increasing splendor of the second period, and the waning of the third. The sun himself presents unmistakably the aspect **D** or **E**, which is alike for both periods. Guided by the belief that its temperature has for some thousands of years been nearly constant, we must assume that its splendor is near its maximum, or else that the process of change is very slow. It is, therefore, needful that we discuss the conditions of the rising atmosphere.

The aspect of every planet is that of the fourth period, wherein a slow cooling and condensation are occurring, the volatiles performing still their cycles of vapor and cloud and falling mist and surface film, amidst the fixity of the unconquerable gases. The moon presents the aspect of the close of this period.* Therefore, we must also discuss the virtually quiescent atmosphere in determining the conditions of the planets and the moons.

* While this theory accounts for the absence of atmosphere about the moon considered as an isolated body, it does not account for the absence of the frozen surface films of the substances, as water, that might be supposed to have constituted its former atmosphere. But we shall see that the theory, as applied to a system of bodies, accounts for the absence of atmosphere in the smaller of these by other means than condensation.

THE OUTFLYING ATMOSPHERE

FOR any mode of expansion of a non-condensible gas,

$$\frac{D\tau}{p} = \frac{D_o\tau_o}{p_o} = \frac{D_h\tau_h}{p} = \frac{D'\tau'}{p'}, \tag{11}$$

wherein D_h, τ_h, p_h, are the values at the time h, or distance r_h, and D', τ', p', are the coincident values of a portion of the gas as determined by experiment.

$$\therefore\ D = \frac{dm}{dV} = D_o \cdot \frac{\tau_o}{\tau} \cdot \frac{p}{p_o}. \tag{12}$$

Because the expansion is adiabatic,

$$\frac{D}{D} = \left(\frac{p}{p_o}\right)^{\frac{1}{\kappa}} = \left(\frac{\tau}{\tau_o}\right)^{\frac{1}{\kappa - 1}}. \tag{13}$$

$$\therefore\ D = \frac{dm}{dV} = \frac{D_o}{p_o^{\frac{1}{\kappa}}} \cdot p^{\frac{1}{\kappa}}. \tag{14}$$

But, $$dV = 4\pi r^2 dr. \tag{15}$$

Multiply (14), (15), member by member :

$$dm = 4\pi \frac{D_o}{p^{\frac{1}{\kappa}}} \cdot p^{\frac{1}{\kappa}} r^2 dr. \tag{16}$$

Since the difference of pressures at any two strata is the weight of the

gas included, added to the force that produces a positive acceleration of the included gas,

$$dp = -\frac{dm}{4\pi r^2}\left\{\frac{dv}{dt}+\frac{m_1}{r^2}\right\} \tag{17}$$

$$= -\frac{D_0}{p_0^{\frac{1}{\kappa}}}\cdot p^{\frac{1}{\kappa}}\,dr\left\{\frac{dv}{dt}+\frac{m_1}{r^2}\right\}, \tag{18}$$

or,

$$p^{-\frac{1}{\kappa}}\,dp = -\frac{D_0}{p_0^{\frac{1}{\kappa}}}\left\{vdv+\frac{m_1dr}{r^2}\right\}, \tag{19}$$

and,

$$\frac{\kappa}{\kappa-1}\left(p_0^{\frac{\kappa-1}{\kappa}}-p^{\frac{\kappa-1}{\kappa}}\right)=\frac{D_0}{p_0^{\frac{1}{\kappa}}}\left\{\frac{v^2-v_0^2}{2}+\frac{m_1}{r_0}-\frac{m_1}{r}\right\}; \tag{20}$$

whence,

$$v^2 = v_0^2+\frac{2\kappa}{\kappa-1}\cdot\frac{p_0}{D_0}\left\{1-\left(\frac{p}{p_0}\right)^{\frac{\kappa-1}{\kappa}}\right\}-2m_1\left(\frac{1}{r_0}-\frac{1}{r}\right). \tag{21}$$

The symbols of pressure and density can be eliminated from this formula by means of the relations established in equations (11) and (13), and m_1 by the relation,

$$g_0 = \frac{m_1}{r_0^2}. \tag{22}$$

So, after reduction,

$$v^2 = v_0^2+\frac{2\kappa}{\kappa-1}\cdot\frac{p'}{D'\tau'}\left(\tau_0-\tau\right)-2g_0r_0\left(1-\frac{r_0}{r}\right). \tag{23}$$

The coefficient of $(\tau_0-\tau)$ can be reduced to a numerical value. Thus, from the fundamental formula,

$$\text{Force}\times\text{time}=\text{mass}\times\text{velocity}, \tag{24}$$

we derive in the C. G. S. system,

$$p'\times 1\text{ second}=\text{mass of 1 gm.}\times\frac{1033.3}{1\text{ sq. cm.}}\times\frac{980.94\text{ cm.}}{1\text{ second}}, \tag{25}$$

wherein p' represents the expansive force in dynes of any gas under a pressure of 760 mm. of mercury at zero temperature, the density and tem-

perature of the gas being what they may. For hydrogen, $D' =$ .00008957, when $\tau' = 273.7°$ of the absolute scale. Divide (25) by D' and the unit of time :

$$\frac{p'}{D'} = \frac{1 \text{ cub. cm.}}{.00008957} \cdot \frac{1{,}013{,}600 \text{ cm.}}{1 \text{ sq. cm.} \times 1 \text{ sec.} \times 1 \text{ sec.}} \tag{26}$$

$$= 11{,}316{,}288{,}936 \times \text{square of unit velocity.} \tag{27}$$

$$\frac{2x}{x-1} = \frac{352}{51}\,. \tag{28}$$

Multiply (27) by (28) and divide by $\tau' = 273.7$. So is obtained

$$\frac{2x}{x-1} \cdot \frac{p'}{D'\tau'} = 285{,}365{,}663 \left(\frac{\text{cm.}}{\text{sec.}}\right)^2, \tag{29}$$

for hydrogen at one degree of the absolute scale. If the relative density of any gas in comparison with hydrogen be δ, then (29) must be divided by δ. It will be convenient to express velocities in terms of kilometers and miles per second. Thus we find for any gas,

$$\frac{2x}{x-1} \cdot \frac{p'}{D'\tau'} = \frac{.0285365663}{\delta} \left(\frac{\text{Km.}}{\text{sec.}}\right)^2 \tag{30}$$

$$= \frac{.0110182}{\delta} \left(\frac{\text{mile}}{\text{sec.}}\right)^2 \tag{31}$$

$$= \frac{(.105)^2}{\delta} \left(\frac{\text{mile}}{\text{sec.}}\right)^2; \tag{32}$$

and equation (23) may now be written

$$v^2 = v_0^2 + \frac{(.105)^2}{\delta} \cdot (\tau_0 - \tau) - 2\, g_0\, r_0 \left(1 - \frac{r_0}{r}\right). \tag{33}$$

Formula (33) shows that the square of the atmosphere's velocity at any stratum is compounded of the square of the initial velocity at which the vapor is delivered from the nucleus, the square of the velocity due to the vapor's adiabatic expansion between the nucleus and that stratum,

and the negative value of the square of the velocity acquired by a particle falling freely from that stratum to the nucleus.

With the last of these we are familiar; let us examine the potency of the second. If hydrogen be emitted however slowly from the nucleus at a temperature no greater than that of boiling water, it will, in expanding to the temperature of freezing water, acquire a velocity of 1.05 miles per second; and the same velocity would be acquired in expanding from zero centigrade to $-100°$ C. If the temperature be that of the oxy-hydrogen blowpipe [about 4000° F. = 2480° absolute], the velocity corresponding to the sinking of temperature to the freezing point of water is five and a quarter miles per second [5.23]. It follows that in the case of comets the effect of gravity upon the atmosphere is generally insignificant in comparison with that of heat; for the velocity acquired by a particle falling from an infinite distance to the nucleus of a comet of 400 miles diameter and of density equal to that of the earth, is no more than the maximum velocity of a cannon-ball [about 1800 feet]. Moreover, we are impressed with the inconceivably high temperature of the sun, that, acting against an enormous intensity of gravity, yet hurls its gases upward with a velocity of hundreds of miles per second.

The velocity, v_o, is always an inconsiderable quantity. Its value is

$$v_o = \frac{m'}{4\pi r_o^2 D_o}. \qquad (34)$$

For instance, if into a body of water at 100° C., and under an atmospheric pressure maintained at 760mm., be injected per square foot of surface per second a quantity of heat equal to that emitted per square foot per second at the sun's visible surface,* then the number of cubic feet of vapor generated per square foot per second, which is also the value of v_o in linear feet, is found by dividing the quantity of heat in pound-degrees by the latent heat of water at 100°, this quotient dividing by the number of pounds of water in a cubic foot, and this quotient multiplying

* Estimated at 2660 pound-degrees. See the section on comets.

by the ratio of the volume of steam to the volume of water at 100°; that is

$$v_o = \frac{2660}{537} \cdot \frac{1700}{62.4} = 135 \text{ feet per second.} \tag{35}$$

Corresponding to the quantity of heat received at the earth's distance from the sun, the value of v_o is only one-46 thousandth as great.

Although the portion of the latent heat expended in overcoming molecular and atomic attractions diminishes at high temperatures, and, perhaps, finally vanishes, the portion expended in external work—the lifting of the entire atmosphere—increases so as to render v_o still less significant. For example, at 200° C. the latent heat of steam is 464 thermal units, and, under the corresponding pressure of 226 pounds per square inch, the volume occupied by the vapor is little more than two cubic feet per pound; so that, if the same quantity of heat be injected as before,

$$v_o = \frac{2660}{464} \times 2.03 = 11.6 \text{ feet per second.} \tag{36}$$

The increase of temperature augments the density more rapidly than the mass vaporized, and so causes (34) to be a diminishing function. v_o may always be neglected.

When we consider the relative values of the components of the square of the actual velocity, whether in forms (21), (23), or (33), we find that the first term, v_o^2, is virtually zero, and that the second term can be greater than, or equal to, but not less than, the third, thus rendering the velocity positive or negative or zero, but not imaginary. The derivation of the second term shows that it is representative of the entire pressure between any stratum and the nucleus, and, therefore, cannot be less than the pressure due to weight alone, but is more when the atmosphere is in motion, retarded, if downward, accelerated, if upward.

The negative value of v does not relate to the voluntarily descending atmosphere, which requires the second term to be less than

the third, but to the case where some extraneous mechanical energy reverses the process, overcoming the intrinsic energy of the vapor. This reversion cannot take place in an isolated body.

Function (33) may be written,

$$\tau_0 - \tau = \frac{2g_0 r_0 \left(1 - \frac{r_0}{r}\right) + v^2 - v_0^2}{(.105)^2} \,.\, \delta\,, \tag{37}$$

or, when r_c is the limit of the atmosphere as a gas,

$$\tau_0 = \frac{2g_0 r_0 \left(1 - \frac{r_0}{r_c}\right) + v_c^2}{(.105)^2} \,.\, \delta\,, \tag{38}$$

wherein v_c is the remaining velocity of the molecular dust. The temperature is independent of the mass and density of the atmosphere, but depends upon its relative density, and upon the actual mass and density of the nucleus.

The work performed per second is

$$\frac{1}{2} m' \frac{(.105)^2}{\delta} \tau_0 = m' g_0 r_0 \left(1 - \frac{r_0}{r_c}\right) + \frac{1}{2} m' v_c^2. \tag{39}$$

This represents the intrinsic energy of the gas, and not the quantity of heat engaged in its formation at the nucleus. The last term is the energy remaining after the atmosphere has been lifted to its limit. If by extraneous power this last amount of energy be injected into the atmosphere, the vapor will be pushed downward, the nucleus temperature and pressure remaining the same.

Condition **C**, to which the foregoing formulæ apply, probably never exists. It is approximated in comets, on account of the small intensity of gravity.

Condition **E** differs from **C** in that the vapors partially condense

before reaching the atmospheric limit. In whatever region this occurs, the formulæ become inapplicable. The density of the mixed vapor and mist remains unchanged at the instant of condensation, while a loss of elastic force, due to the conversion of a portion of the matter to an inelastic state, occurs simultaneously with a gain of elastic force, due to the disengagement of latent heat. So, the ratio of pressure to density, which is a measure of the motive power, changes abruptly. The formulæ are applicable from nucleus through the region of limpidity to the region of condensation; and, beyond this, are, with new values of the constants, more or less applicable as less or more condensation occurs. Formula (38) is applicable when r_c, v_c, are understood to be mean values for the gases, such as make formula (39) still true. For instance, if r_c be a mean of the distances whereat the various portions of ejected matter, whether as dust or vapor, come to rest, then v_c is zero, and

$$\tau_o = \frac{2g_o r_o}{(.105)^2}\left(1 - \frac{r_o}{r_c}\right)\delta. \tag{40}$$

When condition **E** exists, the temperature is high enough to drive the vapors, and, tangled with them, the mists, to vast distances, so that they do not rise and return in short periods, but remain away for ages. When condition **D** exists, r_c is much smaller, and τ, also, less. But, on account of the interference with the falling mist, characteristic of condition **D**, τ_o is greater than the formula indicates, unless allowance for this be considered to be made in the value of r_c.

Evidently, condition **D** can exist, however low the nucleus pressure and temperature, provided there is a virtual vacuum from the limit r_c outward.*

The values of the variables at the surface of the nucleus are in all cases the most difficult to determine by direct observation. In place of these may be substituted the values determined roughly by observation at some superior stratum, r_h, that is, after the vapor has been travelling h seconds from the nucleus. The only difference in the resulting formulæ

* τ_o, in formulæ (38), (40), depends upon the mean value of δ for the congregation of gases; it is, therefore, comparatively great for the lighter gases; hence a residuum of these extends on indefinitely into space.

is that v_h cannot, like v_o, be neglected. By this substitution, formulæ (33) and (37) become

$$v^2 = v_h^2 + \frac{(.105)^2}{\delta}\left(\tau_h - \tau\right) - 2g_h r_h\left(1 - \frac{r_h}{r}\right), \tag{41}$$

$$\tau_h - \tau = \frac{2g_h r_h\left(1 - \frac{r_h}{r}\right) + v^2 - v_h^2}{(.105)^2} \cdot \delta, \tag{42}$$

where the relation of the differences of temperature and velocity is exhibited for any difference of height.

After the nucleus temperature has remained constant for a long time, the conditions existing at each stratum of the atmosphere have also assumed constancy for a vast distance outward,—not indefinitely, for the ascent may be an impulse against a previously falling atmosphere, and it may reach to the confines of other atmospheres, but still for a vast distance. Through each stratum passes the same quantity of vapor per second and the same quantity of mist. Furthermore, from the nucleus to the stratum where the first particles come to rest, the quantity of matter that passes outwardly through each stratum in the unit time is the quantity vaporized at the nucleus in the same time; that is

$$\frac{dm}{dt} = m', \tag{43}$$

or,

$$m = m't. \tag{44}$$

Now, if we consider condition **C**,—the case of a non-condensible gas, and which is approximately the condition pertaining to comets,—we may combine the equation (43) with those previously derived and thus eliminate one of the three variables. But this application cannot be made to conditions **D** and **E** when gravity is great, as in the case of the sun, because the heavy condensation renders a large part of m' inert,

although, as before mentioned, it also increases the energy of the remaining gas. For condensible gases, that is, for the case of nature,

$$\frac{dm}{dt} = m' f(r, I, etc.), \tag{45}$$

a function too imperfectly determined to be used. Let us transform equation (21) by the relation (43), premising that the resulting formulæ, although applicable to comets with some degree of approximation, and to the lower comparatively limpid atmosphere of the sun between nucleus and photosphere, are not applicable to the solar atmosphere as a whole.

By comparison of equations (43), (16),

$$m' = 4\pi \frac{D_0}{p_0^{\frac{1}{\kappa}}} \cdot p^{\frac{1}{\kappa}}\ r^2 v, \tag{46}$$

which, for the nucleus values of the variables, reduces to

$$m' = 4\pi D_0 r_0^2 v_0, \tag{47}$$

a mode of function (34). From (46), (47),

$$\left(\frac{p}{p_0}\right)^{\frac{1}{\kappa}} = \frac{v_0\, r_0^2}{v\, r^2}; \tag{48}$$

whence, by combination with (13),

$$\frac{D}{D_0} = \left(\frac{p}{p_0}\right)^{\frac{1}{\kappa}} = \left(\frac{\tau}{\tau_0}\right)^{\frac{1}{\kappa - 1}} = \frac{v_0\, r_0^2}{v\, r^2}\ . \tag{49}$$

(48) and (21) produce

$$v^2 = v_0^2 + \frac{2\kappa}{\kappa - 1} \cdot \frac{p_0}{D_0} \left\{ 1 - \left(\frac{v_0\, r_0^2}{v\, r^2}\right)^{\kappa - 1} \right\} - 2m_1 \left(\frac{1}{r_0} - \frac{1}{r}\right), \tag{50}$$

by which the velocity is determined for any value of r. When the explicit function of v is placed in equation (49), that equation then determines the values of density, pressure, and temperature at any

stratum in terms of the nucleus values. From (43), (44), (16), is derived

$$m = m't = 4\pi \frac{D_0}{p_0^{\frac{1}{\kappa}}} \int p^{\frac{1}{\kappa}} r^2 dr, \tag{51}$$

which expresses the atmospheric mass between the nucleus and any stratum, and the time required for its generation. Another formula for time is simply derived :

$$t = \int \frac{dr}{v} \; . \tag{52}$$

The values corresponding to r_k can be substituted for the values corresponding to r_o.

Discussion of equation (50) shows that, when the force of gravity is small, the velocity continually increases to an infinite distance, rapidly at first, then very slowly, being virtually a constant a short time after the issue from the nucleus : that, when the force of gravity is great, the velocity may successively increase and decrease, passing through maximum and minimum states between the nucleus and infinity.

Formulæ (46), (48), (49), (50), (51), are not applicable to the sun continuously through the spheres of condensation from the nucleus to infinity.

The quantity of heat generated in the nucleus each second, whether by impact, by contraction, or by other means, to maintain a constant temperature and a constant aspect of the nebula, is itself constant, and expends itself in conversion of the mass, m', into vapor, in imparting to that mass the velocity, v_o, and in pushing back the total pressure, $4\pi r_o^2 p_o$, a distance v_o :

$$Q_1 = m'I_o + \tfrac{1}{2}m'v_o^2 + 4\pi r_o^2 p_o v_o \, , \tag{53}$$

wherein

$$I_o = f_{iv}(\tau_o), \tag{54}$$

the energy spent in molecular work upon the unit mass. This is

approximately zero at high temperatures. The second term of the second member of (53) is always insignificant.

Divide (53) by $4\pi r_0^2$ to find the quantity of heat expended per second upon the unit surface of nucleus, at the same time eliminating m' by the relation, (34).

$$Q_1 = v_0 \left\{ D_0\left(I_0 + \tfrac{1}{2}v_0^2 \right) + p_0 \right\}. \tag{55}$$

The ratio between the amounts of internal and of external work for any substance, or any mixture, is a function of the temperature.

$$\frac{m' I_0}{4\pi r_0^2 p_0 v_0 + \frac{1}{2} m' v_0^2} = f^v(\tau_0). \tag{56}$$

We have altogether the following nine constants involved in the formulæ :

$$r_0 \quad m_1 \quad Q'_1 \quad \tau_0 \quad p_0 \quad D_0 \quad v_0 \quad m' \quad I_0 \,. \tag{57}$$

We have seven equations of relation : (11), when the second and fourth members are considered; (13), which contains but one relation, and in which for D, p, τ, must be substituted, D', p', τ'; (34), (54), (55), (56), and the equation,

$$m_1 = \tfrac{4}{3}\pi r_0^3 D_1 , \tag{58}$$

wherein D_1 is the density of nucleus. Consequently, the diameter and temperature of the nucleus determine the other seven constants, and establish the relation of the variables, provided the component substances and the laws of their latent and specific heats be known.

THE QUIESCENT ATMOSPHERE

WHEN the third period comes to a close and the encompassing vapors are still,

$$\tau_0 - \tau = \frac{2g_0r_0}{(.105)^2} \cdot \left(1 - \frac{r_0}{r}\right) . \delta . \tag{59}$$

This is a transient state. As heat passes by radiation from the nucleus upward to the colder strata, the difference of temperatures diminishes, and, thereupon, the atmosphere commences to descend. Throughout the fourth period of slow and final descent,

$$\left.\begin{array}{c} \tau > \tau_0 - \frac{2g_0r_0}{(.105)^2} \cdot \left(1 - \frac{r_0}{r}\right) . \delta \\ \tau < \tau_0 \end{array}\right\} , \tag{60}$$

until, at the end,

$$\tau = \tau_0 , \tag{61}$$

and motion ceases.

The exact form of function (60) depends upon the laws of radiation, which are not well understood in this case. The atmosphere, as a whole, slowly descends until the nucleus becomes so cool that the more volatile gases, like nitrogen and oxygen, refuse to enter into chemical combinations. The other vapors, continuing to liquefy and solidify, leave the atmosphere almost wholly composed of permanent gases. But the less volatile substances are still surrounded by their vapors, which, on account of the remaining differences of temperatures, rise, condense, and fall, in successive circuits, perceptibly or not perceptibly as their quantities are greater or less. More and more slowly the condition represented by

equation (61) approaches, when the atmosphere becomes quiet forever, composed principally of the uncombined volatile gases, mingled with the vaporous remainders of all the substances yet residing at the surface of the solid globe.

In this finality, equation (11) becomes

$$\frac{D}{p} = \frac{D_0}{p_0} = \frac{D'\tau'}{p'\tau_0}\,. \tag{62}$$

$$\therefore\; D = \frac{dm}{dV} = p\,\frac{D_0}{p_0}\,. \tag{63}$$

Combine with (15):

$$dm = 4\pi\,\frac{D_0}{p_0}\,pr^2dr\,. \tag{64}$$

(17) is now

$$dp = -\,\frac{m_\prime dm}{r^2\,.\,4\pi r^2}\,; \tag{65}$$

which, by combination with (22) and (64), becomes

$$dp = -\,\frac{D_0\,r_0^2\,g_0}{p_0}\,.\,p\,\frac{dr}{r}\,. \tag{66}$$

whence

$$l\left(\frac{p}{p_0}\right) = \frac{D_0\,r^2{}_0\,g_0}{p_0}\,.\left(\frac{1}{r} - \frac{1}{r_0}\right) = l\left(\frac{D}{D_0}\right), \tag{67}$$

or,

$$p = p_0\,e^{\frac{D_0\,r^2{}_0\,g_0}{p_0}\,.\left(\frac{1}{r} - \frac{1}{r_0}\right)}\,. \tag{68}$$

The density of the gas diminishes rapidly outward. In case of the earth and its atmosphere, let us find the density at a distance above its surface equal to its radius, upon the supposition that the temperature is uniform.* Thus multiply the second and third members of (67) by the

* Sir Isaac Newton made a similar computation to illustrate the tenuity of comets' tails; *Princip.*, lib. iii, prop. 41.

modulus of the Brigg's system of logarithms, and for r substitute $2r_o$; then,

$$log\left(\frac{D}{D_o}\right) = -\frac{M\,D_o\,g_o}{p_o}\cdot\frac{r_o}{2}. \qquad (69)$$

For the earth's atmosphere,

$$\frac{p_o}{M\,D_o\,g_o} = 60{,}345 \text{ English feet.} \qquad (70)$$

Reduce r_o also to feet. Then,

$$log\left(\frac{D}{D_o}\right) = -\frac{4000 \times 5280}{60345 \times 2} = -175; \qquad (71)$$

or,

$$D = D_o\left(\frac{1}{10}\right)^{175}, \qquad V' = V_o'\,(10)^{175}. \qquad (72)$$

Let V_o' be a portion of the air at sea-level density that would fill a sphere one inch in diameter. Now if R represent the radius of the spherical volume occupied by the same mass at the density existing, according to the above presentation of the law, at a distance equal to the earth's radius above the earth's surface

$$\frac{4}{3}\pi R^3 = \frac{4}{3}\pi\left(\frac{1}{2}\right)^3 (10)^{175} \text{ cubic inches,} \qquad (73)$$

and

$$R = \tfrac{1}{2}\,(10)^{58} \text{ inches,} > (10)^{53} \text{ miles}; \qquad (74)$$

that is, the volume would include the visible universe.

We cannot assume that the accepted laws of expansion, even isothermal, are true to such extremes; yet it is evident that the permanent gas attaching even to large condensed masses, consists of a mere film.

Functicn (68) may be set in this fashion,

$$\frac{D_o}{D} = \frac{p_o}{p} = e^{\frac{D'\tau' g_o r_o}{p'\,\tau_o}\cdot\left(1-\frac{r_o}{r}\right)}, \qquad (75)$$

by which it is seen that, as the nucleus temperature is less, the ratio of densities at the nucleus and at any stratum above, departs from unity; as

either the mass of the nucleus, or the relative density of the atmosphere, is less, the densities return toward uniformity. Two bodies of equal dimensions, whose masses are in the same ratio as their temperatures, immersed in the same thin fluid, are surrounded by atmospheres varying equally in density from the nucleus outward.

Formula (75) shows that the density at each stratum varies as the surface density: hence, the surface density varies as the atmospheric mass: consequently, if a body be immersed in an infinitude of ethereal fluid, it will attract to itself an atmosphere whose eventual surface density will depend upon the original uniform density, D'', of the pervading fluid in such a way that

$$\frac{D_0}{D''} \text{ is constant.*} \tag{76}$$

The extreme effect of the body upon the fluid is indicated by

$$\frac{D_0}{D_\infty} = e^{\frac{D'\tau' g_0 r_0}{p'\tau_0}}, \tag{77}$$

which increases with the mass, but far more rapidly. A small body, as a planetoid or meteor, so little disturbs the uniformity of the fluid in which it is immersed, that it gathers therefrom no appreciable atmosphere, nor can it hold an atmosphere of its own generation.

These formulæ are true only upon the suppositions that the fluid is infinitely expansible, receives unlimited heat, has been approaching the quiescent adjustment for an endless time, and possesses no molar attractions between its own portions. While indicating the conditions existing near the nucleus with considerable accuracy, they are entirely erroneous when applied at vast distances.

* Equations (64), (68) determine this constant.

THE SOLAR ATMOSPHERE

TO the unaided eye the sun appears like a ball of fire, emitting a most vivid light. It is to be judged from this that the sun is not in condition **A**, because that is accompanied by a dull red light; not in condition **B**, because that is transient; not in condition **C**, since that is always improbable; nor yet likely to be in condition **D**, because the cycles are then too small and slow to cause a vivid light; but that it is likely to be in condition **E**.

When through powerful telescopes this body is more closely viewed, its visible surface is seen to be composed of a stratum of fiery vapors. The surface is not uniform in brightness, but consists of multitudes of brilliant dots and streaks. The brighter of these are ridges rising thousands of miles above the general surface, fixed neither in position nor in form. Through vast rents in this shell of clouds its meagre thickness,—of 300 to 3,000 miles,*—becomes apparent, resting upon a darker atmosphere. The spots are evanescent, and ever varying in appearance. As they traverse the disc in different latitudes, they reveal a diversity of angular velocity of rotation. On this evidence, conditions **A**, **B**, and **C** must be at once dismissed. The sun is either in condition **E** or condition **D**.

Since conditions **E** and **D** are similar in nature, differing only in intensity, it must rest a matter of judgment based upon the facts, whether the material ejected by the sun is cast beyond the limits of the solar system, or never reaches to the orbit of the earth.

The vividness of the light emitted by the cloudy stratum indicates a

* Young's *Astronomy*; ed. 1889, p. 187; Chamber's *Astronomy*; ed. 1889, p. 53; etc.

tremendous outflying velocity of the atmosphere. The density* and thickness of the shell are so small that the quantity of matter contained at any instant seems insufficient to dispense the solar rays for more than a few seconds of time. If the summit of flight of the incandescent matter were but little above this stratum, the supply of light-producing material would be so slow, and the proportion of exhausted falling material so great, that it is inconceivable how so intense a light could be maintained. But, if condition E exists, the phenomenon is explainable as the incandesence of a moderate quantity of matter per second, not requiring that each particle should glow intensely for longer than a few seconds. So, were the outflow to cease, the photosphere would vanish like a flash, or like a flame from which the gas is suddenly cut off.

On its passage from the nucleus, the ascending atmosphere condenses in a succession of layers, separate or contiguous. In comets, because of the variation of temperature, one after another of these layers dominates, and all move outwards. In the sun they remain fixed, and one dominates constantly, obscuring those within and overpowering those without.

In a body so intensely heated as the sun,† the first condensations cannot be of gases into their own liquids or solids, but must be chemical combinations of elements into compounds that are still gaseous,—perhaps of ultimate elements to form the so-called chemical elements.

The inner spheres of condensation have a small portion of incandescent matter and a large portion of dark matter. Their pores and spots, if not larger, are far more numerous. The spheres contain a minor quantity of light, and their matter has a minor velocity. The principal sphere of condensation occurs where a temperature is reached by adiabatic expansion that permits the majority of substances to condense.

But there still remain gases too volatile for condensation, whether these are products of previous condensations, or spring originally from the nucleus ; and these, with the incandescent vapors, passing through the principal sphere, produce light and dark specks upon its surface, and striæ

* Wullner, from spectroscopic observation, estimates that the pressure close by the solar disc lies between two inches and twenty inches of mercury.—Proctor's *Orbs around us*, p. 269.

† The solar rays collected by a lens volatilize the most refractory substances,—gold, platinum, and even fire-clay.

in those sections made apparent by the outflow of such great volumes of volatile gases as break the continuity of light.

On account of the violence and non-uniformity of the heat generated in the photosphere, it is to be expected that the superior realms of condensation, for some little distance outward, are irregular, fragmental, and not stationary.

If the theory be true that the entire photosphere is traversed with enormous velocity by vapors condensing into less elemental vapors, there should exterior to it be a broad layer of gases possessing still an enormous velocity of ascent. Now, when the moon covers the sun and hides his dazzling brightness, around their common rim appears the continuous region of the "Red-flames,"—the "Sierra," or "Chromosphere." The spectroscope reveals that this is largely composed of hydrogen gas. Out of this rise the "Prominences," or "Protuberances,"—mountains of flame,—to the height, sometimes observed, of 400,000 miles, and with a velocity of 250 miles per second.*

The theory of a swift outflying atmosphere not only explains the phenomena of the photosphere and the sierra, but answers a question that has hitherto been perplexing. Its statement is found in the following paragraph from Chamber's *Astronomy*, 1889, pp. 6,7 :—

"A consideration of the comparative lightness of the matter composing the Sun led Sir J. Herschel to think it 'highly probable that an intense heat prevails in its interior, by which its elasticity is reinforced, and rendered capable of resisting [the] almost inconceivable pressure [due to its intrinsic gravitation] without collapsing into smaller dimensions.' That the internal pressure exerted by the gases imprisoned within the luminous surface or photosphere of the Sun, must be absolutely stupendous, we have evidence of in the fact of the almost inconceivable velocity (100 to 200 miles per *second*) of the uprushes of incandescent gas and metallic vapors, which are almost constantly taking place at various parts of its surface. It would seem all but certain that the Sun is nearly wholly gaseous, and that its photosphere consists of incandescent clouds, in

* *Encyc. Brit.*; Art., *Sun*; p. 650.

which the aqueous vapor of our terrestrial clouds is replaced by the vapors of metals. These considerations, however, introduce a difficulty of a precisely opposite character to that which Sir J. Herschel essayed to combat; inasmuch as, in the light of our present knowledge, it seems hard to conceive how a mere shell of metallic vapor should be able to confine gases at the incomprehensible pressure at which those which rush out in the form of the now well-known 'Red Flames' must be confined."

The theory requires that the atmosphere shall extend beyond the chromosphere, and still be composed of gases, eventually mingled with the dust of their partial condensation, all flying outward. The presence of dust is to be revealed, not only in the visibility of the upper strata, but in the polarization of the light thence proceeding, and, when viewed through prisms, by the reflected spectrum of the sun. The gases, so long as they remain sufficiently heated, are to be made known by their peculiar spectra; the motion, by direct observation, at the chromosphere; thereafter, by radiated and striated structure, and by correspondence of structure between the remote and inner layers.

Through the clear air of Colorado, Professor Langley and his colleagues, during the eclipse of 1878, traced the corona to a distance of at least nine million miles from the sun.* The corona consists of luminous gas and "dust," or "mist," or "fog."† The spectrum of the gas, "Coronium," shows one faintly bright greenish line, the "1474 Kirchhoff."‡ As a background, the spectrum shows the faint continuous spectrum of the sun including its dark lines, thus indicating a reflection of solar light.‖ "The inner corona is usually composed of bright striæ or filaments separated by darker bands, and some of these latter are sometimes seen to be almost totally black. The appearances are extremely irregular, but they are often as if the inner corona were made up of brushes of light on a darker background."§ "In most instances the rays

* Young's *Astronomy*, p. 209; Newcomb & Holden's *Astronomy*; Ed. 1881; p. 299: etc

† Young's *Astronomy*, p. 209.

‡ Newcomb and Holden, *Astronomy*, p. 305: *Encyc. Brit.*; Art., *Astronomy*, p. 789: *etc.*, *etc.*

‖ Newcomb and Holden, *Astronomy*, p. 305.

§ Newcomb and Holden, *Astronomy*, p. 300.

which extend to the outer part of the corona grow gradually fainter in their upper parts without exhibiting any change of direction." * The corona seems always to be described and pictured as a strongly radiated structure, which shows that centrifugal forces are still paramount. Its connection and continuity with the region of prominences and the sierra are indicated by the fact that rifts in the upper region are traceable downward through the protuberances, and overlie the shallower portions of the chromosphere.† The circumferential continuity of the corona shows that it is due to no local eruptions, but to the nearly uniform sweep of the atmosphere outward. At the same time, the radiated structure and the rifts disprove the theory that it is matter revolving about the sun.

There is still another fact that indicates an outflying motion of the atmosphere, and agrees with the theory, but, otherwise, seems anomalous. From spectroscopic investigations "Lockyer concludes that in all probability the atmospheric pressure close by the sun's surface is not nearly so great as is to be expected if the corona is a solar atmosphere."‡ Now, as formula (17) shows, the pressure transmitted from each infinitesimal layer is its weight increased by the acceleration of its outward velocity, or diminished by the retardation of its outward velocity. It can easily be shown that the maximum velocity of an atmosphere forced to rise by heat from so massive a body as the sun, is reached quite near its surface. This is true also of the liquid or solid particles. Hence, the velocity of the corona is decreasing; its differential is negative; gravity is employed in over-coming *vis viva*; the pressure at the photosphere is less than the weight of the incumbent air. The greater the difference between this pressure and this weight, the greater is the sum of the infinitesimal differentials of velocity; that is, an obviously great difference between the pressure and the mass denotes a great velocity at the photosphere.

The very visibility of the corona to a distance of nine million miles denies its existence as a quiescent atmosphere, as an application of

* Chamber's *Astronomy*, p. 311.

The last two quotations are taken from paragraphs that contain mention of curved rays sometimes seen. The sentences selected describe the usual appearances of inner and outer corona.

† Proctor's *Orbs around us*, p. 269.

‡ Proctor's *Orbs around us*, p. 269.

equation (75) reveals,* and because the dust would not be then sustained; whereas the first and fourth members of equation (49), which are independent of the mode of expansion, show that the density of gas and dust, at twenty times the distance of the chomosphere from the centre, is as great as one hundredth the density of the chromosphere, in an ascending atmosphere, when the velocity has been diminished by three quarters, and cannot be less than one 400th.

The theory of the atmosphere in condition **E** or **D**, surrounding a nearly uniformly heated nucleus, shows that it is impossible for any gaseous matter to descend. Observers of the sun have often seen uprushes of matter, but, (so far as the author's research extends,) have never witnessed a downfall. The motions of the spots invalidate the theory that these rents are caused by downflows; for, if we suppose, for the sake of argument, that the poles are so much cooler than the equator that the rising tendencies at those parts are overwhelmed by the gravity of the volumes emitted at the middle zones, then the descending streams acquire greater and still greater angular velocities as they pierce the shining envelope farther and still farther from the equator, and the angular velocity of the spots must increase with the latitude. The reverse is the fact. If we premise that the poles are so much hotter than the equator as to cause the polar outflows to descend in lower latitudes, still the angular velocities of the spots must increase with the latitude. The reverse is the fact. Therefore, the spots cannot be caused by descending matter that has been ejected in any latitude other than their own. When restricted thus narrowly, the theory of gaseous downfalls loses plausibility, because it does not explain why the inflows should prevail in particular zones.

It has been noticed that when spectroscopic lines cross a sun-spot, these are bent sometimes one way, sometimes the other. This has been considered to indicate an ascent or descent of gases; but the tacit assumption has been that the photosphere is a virtually quiescent shell of

* A temperature approaching 10,000,000 degrees is required to exist in the photosphere without replenishment in order to keep the density at 9,000,000 miles, one hundredth of that in the chromosphere, according to formula (75).

light. In view of the theory here developing, the deviation of the lines indicates a difference in velocity of the matter emitting luminous rays from the spot, and from its borders, and not a descent of the former, unless the deviation be sufficient to represent a difference of velocity greater than perhaps 250 miles per second. When the volatile gases rising in the region of the spot are so transparent that the interior minor spheres of light are visible through them, a less velocity should be shown. When the light comes from the gases themselves, a greater or less velocity should be marked.

Evidence favors the belief that the appearance of spots marks the augmentation of solar activity. A great local increment of energy, whether by subsidence or by implunging of matter, would first eject large volumes of volatiles with increased velocity. These would bore through the spheres of light, presenting the phenomena of dark spots, while the surrounding matter, sharing somewhat in the increments of velocity and density, would in condensing emit intenser light, a circumstance quite frequently observed.* Upon reaching the inferior surface of the photosphere, the dark gases should have the greater speed; but, on the other hand, the condensing vapors should, in the limits of the shining sphere, develop a greater heat, as is observed to be the case,† and, usually, a greater velocity.

The form of the outbursting volatile gases should be that of a spindle, its surface not sharply defined from the surrounding condensible vapors. As the foremost point breaks through the photospheric shell, the aspect from without should be a ragged black opening without penumbra; but, as the parallel and the receding sides are passing, a penumbra should be seen, due to the mixture of condensible and volatile gases that forms

* "In addition to spots, streaks of light may frequently be remarked upon the surface of the sun toward the equatorial margin of the disc. These are termed *faculæ*, and are generally found near spots (just outside the penumbra) or where spots have previously existed or are soon about to appear." . . . "They are of irregular form and may be likened somewhat to certain kinds of coral, and are more luminous than the solar surface surrounding them." . . . "They are elevations or ridges in the photosphere." . . . "Prominences give gaseous, *i.e.*, bright line spectra; faculæ continuous spectra."—Chamber's *Astronomy*, pp, 45, 46.

† "Secchi has shown that the heat radiated from the spots is less than that from the disc generally."—Chamber's *Astronomy*, p. 43; Newcomb & Holden, *Astronomy*, p. 286; *etc.*

the boundary of the spindle. Finally, as the lower tapering end approaches, the umbra should disappear, and the dwindling penumbra still linger for a time. Such is, indeed, the history of a sunspot.* A descending volume of dark gas would first break the exterior surface of the shell, causing the penumbra to appear first, and then the umbra, the order of phenomena reversed.

The rising streams of transparent volatiles are curved, because of the rotation of the sun's substance; this, in all likelihood, prevents visibility of the nucleus through any single stream. On account of the interior minor spheres of condensation, whose existence the theory indicates, it is extremely improbable that the nucleus, even if it possess a definite surface, is ever seen, as its apparition would require a series of spots to lie in one straight line, and that this should be the line of vision.

The atmosphere itself, from nucleus to photosphere, must be nearly regular in constitution, the powerful forces causing its outflowing little affected by the first comparatively slight condensations. This regularity, continuing through the photosphere, ceases in the sierra, but tends to return in the outer regions.

Undoubtedly, the variation in angular velocity of the spots according to their latitude, their congregation almost wholly in two particular symmetrical zones, and the cycle of frequency and infrequency of their appearance, form a clue to the shape, size, rotation and constitution of the nucleus, though, at present, we cannot follow it. The law of the variation of angular velocity, as determined by numerous observations, is thus empirically expressed by Carrington,

$$X = 865' - 165' \sin^{\frac{7}{4}} l, \tag{78}$$

* "It is not till it has attained some measurable size that a penumbra begins to be formed—a circumstance strongly favoring the origination of the spot in a disturbance from below, upward; *vice versa*, as the spots decay they become bridged across, the umbræ divide, diminish in size, and close up, leaving the penumbræ, which, by degrees, also contract and disappear. The evanescence of a spot is usually more gradual than its formation."—Chamber's *Astronomy*, p. 24.

and thus by Faye,

$$X = 862' - 186' \sin^2 l, \qquad (79)$$

wherein X is the daily angular motion, and l is the latitude.* We cannot think that this is due to similar variations of angular velocity in the zones of a solid, liquid, or compact gaseous nucleus. Then it must be due to a curving toward the equator of the ascending gas. If, then, we consider what conditions will compel all the particles of the out-forced vapors to follow tracks that are convex toward the axis and concave toward the equatorial plane, we readily find one that is not only adequate to do this, but that our manifold experience teaches us certainly exists in the unseen nucleus. We need no sight of it to be sure that the sun's core rotates, and that, consequently, it is oblate. The vapors rising from a nearly uniformly heated oblate spheroid, whether in rotation or not, flow outward in curves concave to the equator's plane, because lateral expansion invariably occurs from the flatter portions of the surface toward the salient. In the case of a disc, some of the vapor paths would bend through more degrees than a quadrant's arc. Thus, the phenomenon of the variable motion of the sun-spots is adequately explained in kind, as being due to the oblateness of the nucleus, but not in degree, so that we might say this cause alone accounts for the entire variation. Indeed, a certain symmetrical distribution of heat, with the equator cooler than the poles, is alone adequate to account for the phenomenon, whereas a symmetrical disposition from a hot equator to a cooler pole would produce a variation of the opposite kind. But, at the surface of the nucleus exist, also, regular and symmetrical variations from equator to poles in the intensity of gravity, and, consequently, in gaseous pressure; and, probably, in the proportions of constituent substances, and, consequently, in relative densities, specific and latent heats. All these causes render the problem too complex for present solution,—not in the deduction of results from data, but in the uncertainty of the data themselves.

It is unnecessary here to deduce formulæ for the paths of the particles outsweeping from the sun, which, on account of oblateness and

* Young's *Astronomy* 177.

rotation, are lines of double curvature; it is sufficient for the purpose of this essay to have shown that symmetrical variation in angular motion of the sectors of an atmosphere, is an inevitable concomitant of an atmosphere of vapors generated and expelled by heat from a rotating nucleus, and that, therefore, the observed variation in angular motion of the sun-spots is evidence of an out-flying atmosphere, unless the same phenomenon can be shown to be a concomitant of a quiescent or descending atmosphere. *

The outflying velocity of the vapor is a measure of the temperature of the nucleus. Formula (37) is

$$\tau_o - \tau_a = \frac{\delta}{(.105)^2} \cdot \left\{ v_a^2 + 2g_o r_o \left(1 - \frac{r_o}{r_a}\right) \right\}, \tag{80}$$

when r_a, τ_a, v_a, are the values at the interior surface of the photosphere. In order to obtain rough numerical estimates, assume $v_a = 200$ miles per second. δ is best assumed to be unity, since observation indicates that a vast proportion of the atmosphere is hydrogen, and that even lighter gases may be contained. On these assumptions, the temperature of the nucleus is 3,630,000 degrees higher than that of the inferior surface of the photosphere, when gravity is left out of count. With r_b to represent the radius of the outer surface of photosphere, we have

$$r_b = 433{,}100 \text{ miles}, \quad g_b = 894 \text{ feet}; \tag{81}$$

$$\therefore \quad 2g_b r_b = 146{,}700, \tag{82}$$

or

$$\sqrt{2g_b r_b} = 383 \text{ miles per second}. \tag{83}$$

Let

$$\frac{r_a}{r_b} = \frac{99}{100}; \text{ or } r_b - r_a = 4331 \text{ miles}. \tag{84}$$

* Some investigations by the author indicate that the rational formula should have the shape,

$$X = \frac{X'}{1 + E \sin^2 l},$$

where X' is the equatorial angular velocity of the photosphere, and E is a function of the eccentricity of the nucleus, and of the variations of heat, pressure, relative densities, latent and specific heats, from the equator to the poles. If the nucleus were a sphere uniformly heated and constituted, E would be zero, and X constant.

This is greater than any observed thickness of photosphere (including penumbra), and insures that the rising atmosphere at r_a is not greatly affected by the newly generated heat of condensation. Then

$$2g_a r_a = 148,180; \quad \sqrt{2g_a r_a} = 385. \tag{85}$$

If $r_o = \frac{4}{5} r_a$, the second term in parenthesis, of equation (80), is $\frac{1}{4}(2g_a r_a)$, or 37,045, and

$$\tau_o - \tau_a = 7,000,000. \tag{86}$$

If the radius of the nucleus be $\frac{1}{2} r_a$, its excess of temperature is 17,000,000 degrees.

In these estimations there can be no pretence to a close approximation to the truth. The sources of error are the imperfect determination of velocity, the fact that the heat generated in the photosphere causes a back pressure that should be added to gravity, the want of knowledge of the nucleus' diameter, and of the constitution of the atmosphere, and, finally, the assumption that the laws of adiabatic expansion determined for familiar temperatures, remain the same for very high temperatures. Like sources of error pervade other methods of estimation. Secchi deduces for the temperature of the Sun 6,100,000 *; Waterston, 7,156,000 †; Soret, 10,000,000 ‡; other investigators, values ranging from 50,000 to 1,500 degrees.‖ All these results are based upon the relation between temperature and intensity of radiation, and differ so widely on account of the dis-similarity of the laws assumed, and the difference in the assumed values of the absorptive powers of the sun's envelope. The values here quoted relate chiefly to the heat generated in the photosphere, since the dense atmosphere beneath seems to absorb nearly all the light from the inner regions, and, presumably, the heat: the estimate of this paper refers to the nucleus, avoiding entirely the heat of the photosphere.

* Newcomb and Holden, *Astronomy*, p. 286.

† Agnes M. Clerke, *History of Astronomy during the Nineteenth Century*.

‡ Ibid.

‖ Young's *Astronomy*, p. 221.

The variations in density, pressure, and temperature, of the nether atmosphere, appear in the following formula, re-stated from equation (49):

$$\frac{D}{D_a} = \left(\frac{p}{p_a}\right)^{\frac{1}{\kappa}} = \left(\frac{\tau}{\tau_a}\right)^{\frac{1}{\kappa - 1}} = \frac{v_a r_a^2}{v r^2}. \tag{87}$$

This is approximately true from the under surface of the photosphere down to a section not too near the nucleus. Let us estimate the ratio of temperatures at the section where the velocity is one mile per second and at r_a. The former section is so near the nucleus that the ratio of the squares of the radii in the last term of equation (87) is little different from the same ratio when r_o is substituted for r. Hence,

$$\frac{\tau}{\tau_a} = \left\{\frac{200 \times r_a^2}{1 \times (\tfrac{4}{5} r_a)^2}\right\}^{\kappa - 1} = (312.5)^{\frac{2}{5}} = 9.9527. \tag{88}$$

Therefore, approximately,

$$\tau - \tau_a = 7{,}000{,}000; \ \frac{\tau}{\tau_a} = 10; \tag{89}$$

whence,

$$\tau_a = 780{,}000, \ \tau = 7{,}780{,}000, \tag{90}$$

the latter being nearly the temperature of the nucleus, under the various assumptions.

$$\frac{p}{p_a} = (312.5)^{\frac{7}{5}} = 3110, \tag{91}$$

so that, if the pressure at the photosphere be one third of an earth's atmosphere,* the pressure near the nucleus,—of the assumed diameter,—is about one thousand terrestrial atmospheres.

* Wullner's estimate of the pressure close to the solar disc is a value between two inches and twenty inches of mercury.—Proctor's *Orbs Around Us*, p. 269.

The ratio of the densities is

$$\frac{D}{D_a} = 312\tfrac{1}{2}. \tag{92}$$

If Wullner's estimate of pressure is to be trusted for such excessive temperatures, the density of the atmosphere both at the photosphere and at the nucleus must be exceedingly small. If the photosphere be ten million degrees in temperature, and the pressure one tenth of an earth's atmosphere, the density of the hydrogen is only

$$D_b = .000008957 \times 273.7 \div 10{,}000{,}000 = .000000000245, \tag{93}$$

which, again, requires a swiftly outflying atmosphere to maintain the vivid light; for, it would be impossible for so rare a medium, virtually quiescent, to emit the solar rays for longer than a few seconds.

Upon the size of the nucleus we can merely speculate, at present. By the analogy of comets we might suspect that the nucleus is small; but we know that the tremendous force of gravity exhausts heat rapidly and holds the spheres of condensation close to the central ball. That this central globe of the solar system should, at planetary temperatures, be very dense, and, therefore, small in comparison with the visible sphere, is true; but, in contravention, the intensity of heat should render it rare, and, so, comparatively large. The rate of variation of the sun-spots indicates a small nucleus; for, since this variation depends upon the curving toward the equator of the escaping streams, it is greater as the distance to the nucleus is more, for the reason that the angular velocity of rotation of nucleus and, therefore, its oblateness, increase as its size is less, and because the deflection of the streams increases with their length. If we could determine the composition, velocity, and temperature of any stratum of the atmosphere, the diameter of the nucleus would be made known, approximately, by formula (50), thus re-stated,

$$v^2 = v_a^2 + \frac{(.105)^2}{\delta} \cdot \tau_a \left\{ 1 - \left(\frac{v_a r_a^2}{v r^2} \right)^{\kappa - 1} \right\} - 2 g_a r_a \left(1 - \frac{r_a}{r} \right). \tag{94}$$

For instance, if we could say,

$$v_a = 200, \quad \tau_a = 1{,}000{,}000, \quad \delta = 1\,;$$

then, knowing that

$$r_a = \frac{99}{100} \times 433{,}100, \quad 2g_a r_a = 148{,}180, \quad \varkappa = 1.4,$$

and placing $v = 1$, we could write

$$r + [4.480781]\, r^{\frac{1}{2}} = [5.815508], \tag{95}$$

where the values in brackets are the logarithms of the co-efficients ; and from this could easily extricate the value

$$r = 282{,}000 \text{ miles.} \tag{96}$$

We can be more sure as to the shape of the sun's core. That it is surrounded by permanent rings of matter is extremely improbable, because such rings must rotate faster than the nucleus in an atmosphere that rotates more slowly than the nucleus. General analogy and the law of variation of sun-spots both point to an oblate spheroid as the shape of the sun's nucleus.

The theory requires that the atmosphere shall extend beyond the visible limits of the corona, and that the dust itself shall be carried on if condition **E** exists. The aspect of the corona as a gradually fading halo of indefinite outline promises that visibility can be pushed far outward by the obscuration of the inner, brighter parts. This happens when the earth rolls her big shoulder between us and the sun. Were there no terrestrial atmosphere, the corona would appear when the sun's orb had only set, reaching upward, and fading away in view of the greater light near the horizon ; progressively, the corona would be encroached upon from centre outward by the earth's dark rim, and would rapidly increase upwards, and this would continue until the light of the stars alone should

suffice to render the utmost limits invisible. But the existing atmosphere, refracting and reflecting, bending and mixing the solar rays, does not permit the lower corona to become visible after the photosphere has sunk; nor the next superior strata when the lower strata are beneath the horizon, nor yet the higher strata, until the orb and its bright immediate surroundings have proceeded far on their journey to the nadir, and the atmosphere no longer holds their bended light. Then appears the faint tapering of a luminous ellipsoid of indefinite outline, whose plane is the plane of the zodiac and whose centre is the sun. It has been seen after sunset and before sunrise of the same night, reaching more than 100 degrees from the sun; it has been witnessed simultaneously east and west as it compassed our globe, and it has even been seen arching completely the midnight sky. *

Formula (49) shows that the density of the sun's atmosphere in condition **E** at the earth's orbit is one hundredth part as great as at the extreme observed limits of the corona,—9,000,000 miles,—even if the velocity has not diminished. But the velocity has certainly dimished, unless the temperature of the sun is many times greater than the greatest estimate yet put in figures; hence the density at the farther region is greater than the one hundredth part of that at the inner region. Now, the sun's atmosphere at 9,000,000 miles is visible through the terrestrial air illuminated by the inner corona; hence the theory demands the existence of a visible solar atmosphere at the distance of the earth's orbit and beyond, when the inner, brighter portions are obscured.

That the Zodiacal Light and the corona are parts of one continuous body appears otherwise probable.

The hiatus in the visible connection between the two parts is fully explainable by the effects of the earth's atmosphere upon the light proceeding from a body that decreases rapidly in brightness from centre outward.

The spectroscopic appearance of the Zodiacal Light is similar to that

* Chambers' *Astronomy*, pp. 142–147: *Encyc. Brit.*; Art., *Zodiacal Light*: etc., etc.

of the corona, indicating, principally, a reflection of the sun's rays,—from minute specks, according to Ranyard. * Other observers have obtained indications that it is composed, also, of self-luminous gas. "Angström, observing at Upsala in March, obtained the bright Aurora line, W. L. 5567, and concluded that in the Zodiacal Light there was the same material as is found in the Aurora and in the solar corona, and probably through all space." † But, owing to the faintness of the light, it has generally been doubted that the bright lines indicating luminous gases were really derived from the Zodiacal Light, the suspicion being that the lines were caused by faint auroras. ‡

The lenticular shape of the Light corresponds with that of the corona, which is often seen with vast equatorial extensions; both of these correspond with the curving toward the equatorial plane of the escaping vapors, as indicated by the variation in angular velocity of sun-spots, and sometimes actually seen in the polar rifts. If it can be shown that the extension of the Zodiacal Light varies with that of the corona, their connection will be established.

Having traced the visible atmosphere uninterruptedly from the sun's surface to a distance of nine million miles, and thence interruptedly to the earth's orbit and beyond, we can now, roughly at least, estimate the temperature of the photosphere. Formula (37) becomes

$$\tau_b - \tau = \frac{\delta}{(.105)^2} \left\{ v^2 - v_b^2 + 2g_b r_b \left(1 - \frac{r_b}{r} \right) \right\}, \tag{97}$$

where r_b is the radius of the exterior surface of the photosphere. $r_b =$ 433,100, $g_b =$ 894, $2g_b r_b =$ 146,700. Let $r =$ 92,890,000 miles, and let

* "On December 19 and 20, 1870, when in Sicily, whither he had gone to observe the solar eclipse, Mr. A. C. Ranyard and some friends (Secchi among them) examined the Zodiacal Light through a Savart polariscope. His main conclusion is that the Zodiacal Light consists of matter which reflects the sun's light. He adds, that matter either consists of particles so small that their diameters are comparable with the wave lengths of light, or is matter capable of giving specular reflection."—Chambers' *Astronomy*, p. 146.

† *Encyc. Brit.;* Art., *Zodiacal Light*, p. 797.

‡ *Encyc. Brit.;* Art., *Zodiacal Light*, p. 797.

the velocity and temperature come to nought at that distance. Assume $v_b = 250$, which, consistently with the assumption of $v_a = 200$, allows for an increase of velocity of fifty miles within the photosphere; $\delta = 1$. Then, after reduction,

$$\tau_b = 7{,}580{,}000. \tag{98}$$

As the appearance of the Zodiacal Light fading imperceptibly, indicates that the particles do not come to rest near the earth, let us determine the temperature necessary to drive the matter to infinity. This is little greater, being

$$\tau_b = 7{,}639{,}000. \tag{99}$$

The increase in solar temperature corresponding to any velocity of the atmosphere as it sweeps by the earth, over that necessary merely to lift the atmosphere to the earth, is

$$\delta\left(\frac{v}{105}\right)^2. \tag{100}$$

When $v = 50$, to the temperature noted in (98) must be added 226,900 degrees; and, when $v = 100$, the temperature must be increased by 907,600 degrees. Formula (100) is independent of the velocity at the photosphere; the only uncertain value contained is δ.

Following are some of the estimates of the photosphere's temperature, founded upon the theory of radiation *:

Soret	10,000,000° C
Waterston	7,156,000
Secchi	6,100,000
Ericsson	4,000,000
Rosetti	20,380
Violle	3,000
Pouillet	1,760
Vicaire	1,400

* Agnes M. Clerke's *History of Astronomy during the Nineteenth Century*; Art., *Temperature of the Sun*; Newcomb and Holden's *Astronomy*, p. 286; *etc.*

This remarkable disparity of results arises from the difference in the formulæ assumed to represent the relation between intensity of radiation and temperature, and in the different values assumed for the absorptive powers of the sun's atmosphere and the earth's.

When we consider the original source of the sun's heat, we soon become impressed with the enormously high temperature to which it, not only possibly, but probably reaches. A mass of iron falling to the sun from the earth's orbit, will instantaneously give forth the energy,

$$\tfrac{1}{2}\,mv^2 = g_0 r_0\left(1 - \frac{r_0}{r}\right), \qquad (101)$$

and this divided by the mass, the equivalent of a heat unit, and the specific heat, is the temperature attained by the mass, supposing it finds the sun's material already at the same temperature, and has not encountered a resisting atmosphere. This temperature is 12,865,700,000 degrees. Falling to a nucleus of diameter two-thirds that of the photosphere, the mass would reach a temperature three halves as great. Falling upon a cold body of the same dimensions and density as the sun, the mass would set free energy enough to raise 1,286 times its own mass of surrounding matter to a temperature of ten million degrees; or to a temperature of fifteen million degrees, if it should strike the nucleus of two thirds diameter. After making due allowance for the fact that all the material of a condensing nebula does not fall as far nor with so great an attraction, we still find that the final temperature would be in the billions, if nothing were lost by radiation, mechanical work and dissociation. These three exhaust heat and reduce temperature, but still leave the highest temperature mentioned in this paper a probable value.

Many astronomers believe that the intensity of solar heat dissolves the so-called elements: in this they are supported by the suspicion of chemists, derived from spectroscopic and other phenomena, that the assumed elements are compounds, with none, or few, exceptions. If this be true, the dissociation of chemical elements into ultimate elements, or into simpler compounds, by means of the exalted temperature rendered

possible by gravity, is, alone, sufficient to conserve the heat of the sun, both in quantity and intensity. When molecules of water, whose atomic affinities are already well satisfied, are mingled with molecules of sulphuric acid, whose atomic affinities are also well satisfied, a heat is generated unbearable to the hand. But this is insignificant in comparison with the intensity of heat generated when the constituent chemical elements of water combine to form that substance. This, in turn, should be insignificant in comparison with the temperature reached by the compounding of the ultimate elements of hydrogen. Whatever this temperature may be, it is undoubtedly fixed. It does not seem that the photosphere can receive directly much heat from the fall of meteors or the contraction of matter, but that its existence, heat, and temperature are the results of chemical combinations. If these combinations be of simpler elements than we know, the temperature of the photosphere is incomparable with any temperature produced by combustion on the earth.

Whether the sun is in condition **E** or **D** can, now, be well determined. The gradual fading outward of the corona and the Zodiacal Light belongs only to the former state. If the particles return to the sun, their outward progress must be arrested in one common region,—a shell of no great thickness, because the mingled substances partake of the same velocity so long as all remain gaseous, and those that first condense to mist or dust possess also the greatest outward velocity at the time of condensation, and are then embosomed in a stream of most rapid flow. An expanding stream of gas and dust that flows to infinity must vanish by imperceptible degrees ; a stream that is projected like a fountain only to return, may, in spherical expansion, grow fainter for a space, but will surely aggregate again at the summit of its flight into a shell comparatively dense in mass and luminosity. No such shell appears.

Apart from appearances, formulæ (98), (99), lead us to judge that the atmosphere passes on toward infinity, and does not return. Less than one per cent. excess of temperature is required to drive the vapors on from the earth's orbit to the end of space, whereas, although we have here no formulæ for resistance to aid our judgment, undoubtedly a much

greater excess of temperature would be required to drive the vapors to the limits of the Zodiacal Light against the opposing stream of falling particles. In other words, less energy is required to effect a clearance than to overcome the added resistance of descending rain.

It seems impossible that dust so fine could fall through an atmosphere rising at the rate of hundreds of miles per second. When, some years since, the crater of Mauna Loa ejected quantities of powdered minerals, the particles, tinting the evening skies, filled the air for many months, descending at the rate of a small fraction of an inch per second. Had the atmosphere been continually rising at the same slow rate, the particles would have been fixedly sustained. It is difficult to conceive of particles of almost molecular fineness falling through a stream rising with incredible velocity, even when we allow that the atmosphere is exceedingly tenuous, and the attraction of the sun is great.

Thus, the theory denies with emphasis that the particles can return to the sun after being cast to the limits of the Zodiacal Light; the vividness of the photosphere supports this conclusion; the appearance of the solar atmosphere confirms it. It will be well, moreover, to formulate the peculiar aspect of the sun and his atmosphere in condition **D**.

In order that the impalpable ascending dust may fall again to the sun, the rising velocity must be comparatively small, the limit of flight must be far within the orbit of Mercury, and, beyond the luminous shell of particles virtually still, must extend a thin and limpid atmosphere of little motion. The photosphere must be correspondingly cooler and less sharply defined, the sun itself less bright than now it is. Since no gas returns even in condition **D**, the condensed particles cannot singly and continuously fall through the rising stream. The infinitesimal dust is sustained in the ascending air. The limitary sphere grows in thickness and density: gradually the sun's light darkens and reddens, as it is more and more obscured. At last, the density in the region that marks the summit of the particles' flight, becomes so great that the combined weight of the suspended particles overcomes the resistance: great masses intermittently fall; the solar atmosphere is thrown into convulsions as it clarifies; the light becomes more brilliant as the obscuring sphere is

broken and destroyed. Again and again in regular succession the sunlight is gradually darkened and reddened till it reaches the minimum of brilliancy, and then is allowed to shine more and more brightly till it reaches the maximum again, the process of dwindling from maximum to minimum enduring longer than the process from minimum to maximum. Such is the changing aspect in condition **D.***

It were strange if among the innumerable stars none should be found in condition **D.**

"All stars do not shine with a constant light. Since the middle of the seventeenth century, stars variable in brilliancy have been known, and there are also stars which periodically change in color. The period of a variable star means the interval of time in which it goes through all its changes, and returns to the same brilliancy.

"The most noted variable stars are *Mira Ceti* (*o Ceti*) and *Algol* (*β Persei*). *Mira* appears about twelve times in eleven years, and remains at its greatest brightness (sometimes as high as the 2d magnitude, sometimes not above the 4th) for some time, then gradually decreases for about 74 days, until it becomes invisible to the naked eye, and so remains for about five or six months. From the time of its re-appearance as a lucid star till the time of its maximum is about 43 days (HEIS). The *mean* period, or the interval from minimum to minimum, is about 333 days (ARGELANDER), but this period, as does the maximum light, varies greatly.†

"About 90 variable stars are well known, and as many more are suspected to vary. In nearly all cases the mean period can be fairly well determined, though anomalies of various kinds frequently appear. The principal anomalies are :

First. The period is seldom constant. For some stars the changes of the period seem to follow a regular law ; for others no law can be fixed.

* The aspect of a body in condition **D** already formulated in an earlier portion of this essay, respects the nucleus and the nether atmosphere, including the spheres of condensation, but not the higher atmosphere where the condensed particles come to rest.

† *Mira* changes from white to full red in passing from maximum to minimum. *Am. Cyc.* ; Art, *Star*, p. 311.

Second. The time from a minimum to the next maximum is usually shorter than from this maximum to the next minimum.

Third. Some stars (as *β Lyræ*) have not only one maximum between two consecutive principal minima, but two such maxima. For *β Lyræ*, according to ARGELANDER, $3^d\ 2^h$ after the principal minimum comes the first maximum; then, $3^d\ 7^h$ after this, a secondary minimum in which the star is by no means so faint as in the principal minimum, and finally $3^d\ 3^h$ afterward comes the principal maximum, the whole period being $12^d\ 21^h\ 47^m$. The course of one period is illustrated below, supposing the period to begin at $0^d\ 0^h$, and opposite each phase is given the intensity of light in terms of *γ Lyræ* = 1, according to photometric measures by KLEIN.

PHASE		RELATIVE INTENSITY
Principal Minimum	$0^d\ 0^h$	0.40
First Maximum	$3^d\ 2^h$	0.83
Second Minimum	$6^d\ 9^h$	0.58
Principal Maximum	$9^d\ 12^h$	0.89
Principal Minimum	$12^d\ 22^m$	0.40

"The periods of 94 well-determined variable stars being tabulated, it appears that they are as follows:

PERIOD BETWEEN		NO. OF STARS	PERIOD BETWEEN		NO. OF STARS
1 d. and	20 d.	13	350 d. and	400 d.	13
20	50	1	400	450	8
50	100	4	450	500	3
100	150	4	500	550	0
150	200	5	550	600	0
200	250	9	600	650	1
250	300	14	650	700	0
300	350	18	700	750	1
					Σ = 94

"The color of over 80 per cent of the variable stars is red or orange. Red stars (of which 600 to 700 are known) are now receiving close attention, as there is a strong likelihood of finding among them many new variables.

"The spectra of variable stars show changes which appear to be connected with the variations, in their light.

"Another class of variations occurs among the fixed stars—namely, variations in color, either with or without corresponding changes of magnitude.

"DR. KLEIN, of Cologne, discovered that *α Ursæ Majoris* periodically changes color from an intense fiery red to a yellow or yellowish-red every five weeks. WEBER, of Peckeloh, has observed this star lately, and finds this period to be well established." *

The theory that prevails to account for these phenomena is that the variable stars "are, from some general cause not fully understood, subject to eruptions of glowing hydrogen gas from their interior, and to the formation of dark spots on their surfaces. These eruptions and formations have in most cases a greater or less tendency to a regular period. There is, however, one star of which the variations may be due to an entirely different cause—namely, *Algol*. The extreme regularity with which the light of this object fades away and disappears suggests the possibility that a dark body may be revolving around it, and partially eclipsing it at every revolution. The law of variation of its light is so different from that of the light of other variable stars as to suggest a different cause. Most others are near their maximum for only a small part of their period, while *Algol* is at its maximum for nine tenths of it. Others are subject to nearly continuous changes, while the light of *Algol* remains constant during nine tenths of its period." †

The theory that the variable stars are in condition **D** seems to account better for the changes of color and general redness of these stars; also, for the changes in the spectroscopic aspects, from hydrogen lines, when the star is brightest, (unobscured), to nebula lines, when the

* Quoted from Newcomb and Holden, *Astronomy*, pp. 440 to 443.

† Newcomb and Holden, *Astronomy*, p. 447.

star is least. The theory, like that which prevails, does not seem to explain the variations of *Algol*.

The conclusion to be arrived at from observation of the facts, as interpreted by the theory, is that the sun, and, therefore, presumably, the brighter stars, are in condition **E**, their atmospheres outflying with tremendous, but diminishing, velocity, until they meet in the interstellar spaces; that many of the duller stars are in condition **D**, alternately veiling and revealing their inner spheres of light.

Here we close the discussion of the sun, having followed his atmosphere to its visible limits; but we shall find further evidence of its existence and extension when we come to discuss the atmospheres of the lesser bodies of the solar system.

PLANETARY ATMOSPHERES

THE planets and satellites are all obviously in the fourth period of their existence, the atmospheres slowly descending, the nuclei slowly cooling. The atmospheres of the warm planets, like Jupiter, are abundantly filled with condensible vapors, rising and falling in enormous volumes. Of the cool planets, like the earth, the atmospheres are more quiescent, composed in greater proportion of fixed gases and in less, of rising and falling vapors. The cold bodies, like the moon, have lost their condensible vapors, and, perhaps, the last traces of the volatile gases.

Little is to be said of the planets as isolated bodies : obedient to the sun, their atmospheres are much affected by his disseminated forces. On account of his attraction and their rotation, tides are produced; on account of his heat and their rotation, other tides are produced, sweeping diurnally round their spheres; on account of his heat and their rotundity, currents are kept perpetually in motion, ascending where his rays strike steepest, and falling at the sides, these currents continually deflected by rotation. In the cooler planets the distribution of condensible vapors is much affected by the sun.

The outsweeping solar atmosphere surely, though with exceeding slowness, denudes the planets of their native atmospheres. The rare upper portions are continuously swept away by the passing stream,—imperceptibly, because the sun's atmosphere is infinitesimal in density. Pressure is relieved, the air expands a little and still is swept away. With it go the thin condensible vapors, while the air is replenished by evaporation. Less rain falls than vapor rises, until in the course of ages all the volatiles are blown away, leaving the globe stripped of its atmosphere and seas. Such is the condition of the moon.

PLANETARY MAGNETISM

Planetary Magnetism

IT is probable that the solar dust is electrified, being the product of chemical compositions and decompositions. Let us make the assumption that it is so, and see what follows. If the dust be positively electrified, a single ray of the solar atmosphere acts upon a magnetic or magnetized body in the same manner as a current of positive electricity flowing by conduction from the sun.* The total effect of all the rays upon any point is null in an undisturbed region of the atmosphere. But, wherever a considerable beam is interrupted in its flow by the interposition of a body, the total effect upon a magnetic or magnetized body in the vicinity of the interruption, is not zero, except at the centre line of that beam and of the space through which the beam, if uninterrupted, would pass. In the space of interruption, the effect increases rapidly from this centre line toward the surface of the beam, and decreases slowly from the surface outward indefinitely. The interruption of a beam of flowing matter caused by the interposition of a planet, begins at some distance before the planet is reached, and ends at some distance after the planet is passed, in a manner entirely analogous to the interruption of a stream of water caused by a submerged boulder.

If the planet present always the same face to the sun, the total tendency of the solar atmosphere to induce magnetism in the planet, as a whole, is null. The effect upon free magnetized needles distributed over the planet's surface, as seen from the direction of the sun, is as follows. Each needle turns upon its axis until it becomes tangent to a circle whose centre is the centre of the orb, and so that its north seeking pole is from its south seeking pole in the direction opposite to that followed by the

* Deschanel's *Natural Philosophy*, p. 708.

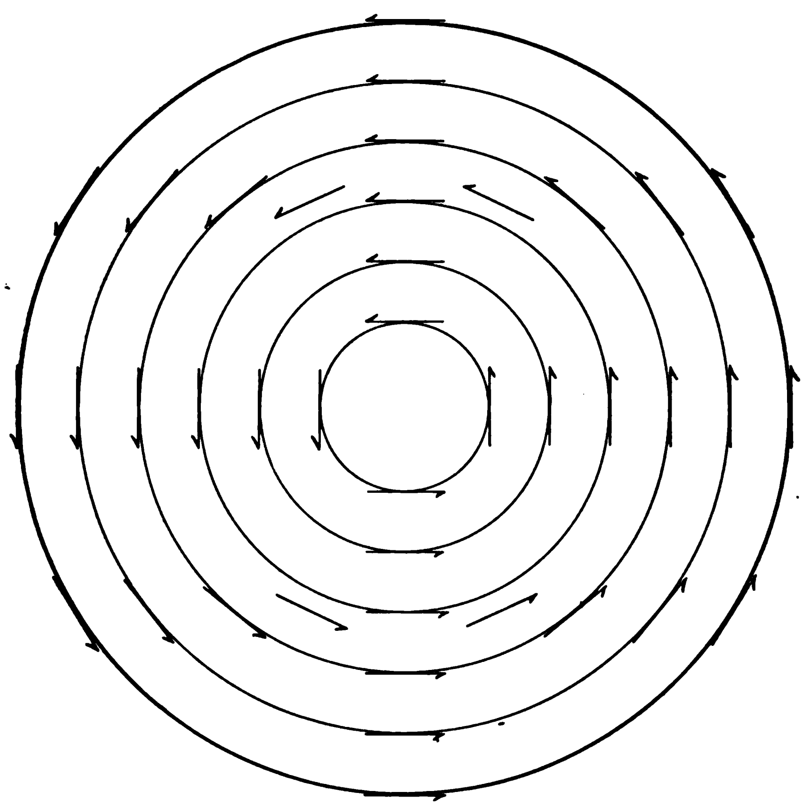
hands of a watch. Thus the needles are ranged in concentric circles, and the intensity of the compelling forces increases from the orb's centre to its rim. The appearance of the needles upon the dark side of the planet is exactly the same, if we could view them through the planet from the sun; but, as viewed from above the dark surface in direction toward the sun, the needles appear to be arranged so that the north seeking pole of each is from its south seeking pole in the direction followed by the hands of a watch.

If the planet rotate, and its axis of rotation, at any time, be normal to the direction of the sun, the tendency of the solar atmosphere, at that time, is to induce magnetism in the planet. Let the direction of rotation be called eastward, and let the extremities of the axis to the left and to the right, as one faces eastwardly, be called, respectively, the north and the south pole. Then the portion of the solar stream that passes the planet on its western side, sweeps by the planet's surface with a velocity greater than that with which the opposite portion sweeps by the eastern surface of the planet. The magnetizing effect upon the planet, as a whole, is the same as that produced by a single, undivided stream of positive electricity flowing by the westerly side of a planet without rotation, in direction from the sun. The magnetizing effect upon the planet is of the same kind as that produced by a current of positive electricity, circling about the planet from east to west; that is, it induces in the north pole the magnetism found in the boreal regions of the earth, and in the south pole the magnetism of the earth's austral regions.

If a small magnetized needle and a comparatively large mass of soft iron be close together in a magnetic field, the needle will be more strongly affected by the induced magnetism in the soft iron than by the original magnetism of the field.* Magnetized needles distributed over

* When a circular disc of soft iron is held in the magnetic meridian, and a small magnetized needle is moved around its rim, the needle is found to be more powerfully affected by the induced magnetic field about the disc than by the original field. That this is not due to permanent magnetism in the disc can be shown by rotating it in its own plane. The induced magnetic field remains virtually stationary, and opposes that of the earth. This

the surface of the planet are affected principally by the induced magnetism of the planet, and in less degree directly by the stream of electrified particles. The former force tends to direct the needles north and south, and hold them fixedly so throughout a whole rotation. The latter force tends to arrange the needles in concentric circles as before explained. As



DIRECTION ASSUMED BY MAGNETIZED NEEDLES UPON A NON-ROTATING PLANET AS SEEN FROM THE SUN.

the planet turns, the latter force continually changes in direction and intensity.

experiment was shown to the writer by Captain Samuel W. Dewey of Philadelphia, an acute practical philosopher. Similar magnetic fields are induced about fly-wheels.

A cylinder of small thickness compared with its diameter, composed of thin soft iron discs, can probably be made the means of magnifying the intensity of the magnetic field in which it may be placed. As the variations in intensity and direction of the forces in the induced magnetic field correspond directly and simply with those of the inducing field, such a cylinder, surrounded by small magnetized needles, might prove to be a more sensitive instrument for noting the variations in terrestrial magnetism than are magnetized needles acted upon by the original field.

The effect of the solar atmosphere acting alone and directly upon the needles is to cause every needle in the northern hemisphere to make one complete rotation with respect to its meridian, in the direction of the hands of a watch, during the time of the planet's complete rotation. Every needle in the southern hemisphere completes a symmetrical and opposite rotation in the same time. Every needle on the equator points due north from noon till midnight, and due south from midnight till noon. As each needle passes from sunrise to noon, and from sunset to midnight, the soliciting force wanes in intensity, increasing, however, from midnight to morn and from noon to sunset. The intensity upon any meridian, except that of sunrise and sunset, increases with the latitude. At the equator it is zero at noon.

The combined effects upon the needles, of the solar atmosphere and the induced magnetism of the planet, result in a cycle of movements that is easily deducible, and that should be exhibited by needles upon the earth at the time of the equinoxes.

A needle at the equator has no diurnal variation of declination, but has a diurnal variation of intensity.

A needle in a northern latitude is from sunrise to sunset continually solicited westwardly of the the planet's true north magnetic pole. Although the intensity of this deflecting force decreases from morn to noon, and increases thence till night, as the needle approaches and recedes from the line passing through the centres of the sun and planet, yet its moment, as applied to the needle, is greatest at midday, where the pull is at right angles to the meridian, and thence gradually decreases both ways, in a manner observable when the meridians are drawn upon the circles of intensity, to zero values in the regions of dawn and nightfall. So, the needle swings westwardly to a maximum declination near noon, and then eastwardly till sunset. Throughout the night the deflection is to the east, and at a maximum at midnight. The changes that occur when the needle has passed to the east of the sun, are slightly,—perhaps imperceptibly,—less decided than the morning changes, because the needle is then affected by a stream of electricity of slightly smaller relative velocity. The nocturnal changes are less decided, because they are

occasioned by the solar stream after its store of electricity has been partially exhausted by contact with the planet's atmosphere.

In the southern hemisphere, the needles throughout the day and night pass through a cycle of changes exactly the reverse in direction of that of their northern counterparts of the same meridians, and exactly the same as that of their antipodes.

The moment of the deflecting force at noon increases with the latitude; hence the diurnal range of declination increases from the equator to the poles.

The solar stream tends to reduce the total horizontal force to a minimum at daybreak, and to cause it to reach a maximum at sunset; through the day it waxes, and through the night it wanes. This was the effect, if the intensity of the stream did not suffer loss by contact with the planet's atmosphere. As it is, both the minimum and the maximum are drawn toward noon, approaching more nearly as latitude increases.

The magnetic force exerted by the solar stream at any point of the planet, has no vertical component, and, therefore, no tendency to change the inclination of a horizontal needle. But its effect upon the dipping needle is apparent. At sunset on the equator, the needle is horizontal; the solar force acts in the same direction as the planetary, simply increasing the horizontal component. Farther north and south in the same meridian, the solar force is acutely inclined to the planetary. Hence it still increases the horizontal force, but diminishes the dip, since its endeavor is to set the needle horizontal. At the poles the magnetic moment of the solar force is a maximum. In the sunrise meridian on the equator, the solar force is exactly opposed to the planetary; hence, it reduces the horizontal force, but has no effect upon inclination, since its moment is zero upon a horizontal needle. Farther north and south, the solar force is obtusely inclined to the planetary; hence, it still reduces the horizontal component, but increases the dip. Upon the noon and midnight meridians the magnetic moment vanishes. Therefore, the dip decreases through the day from a maximum after sunrise, on account of

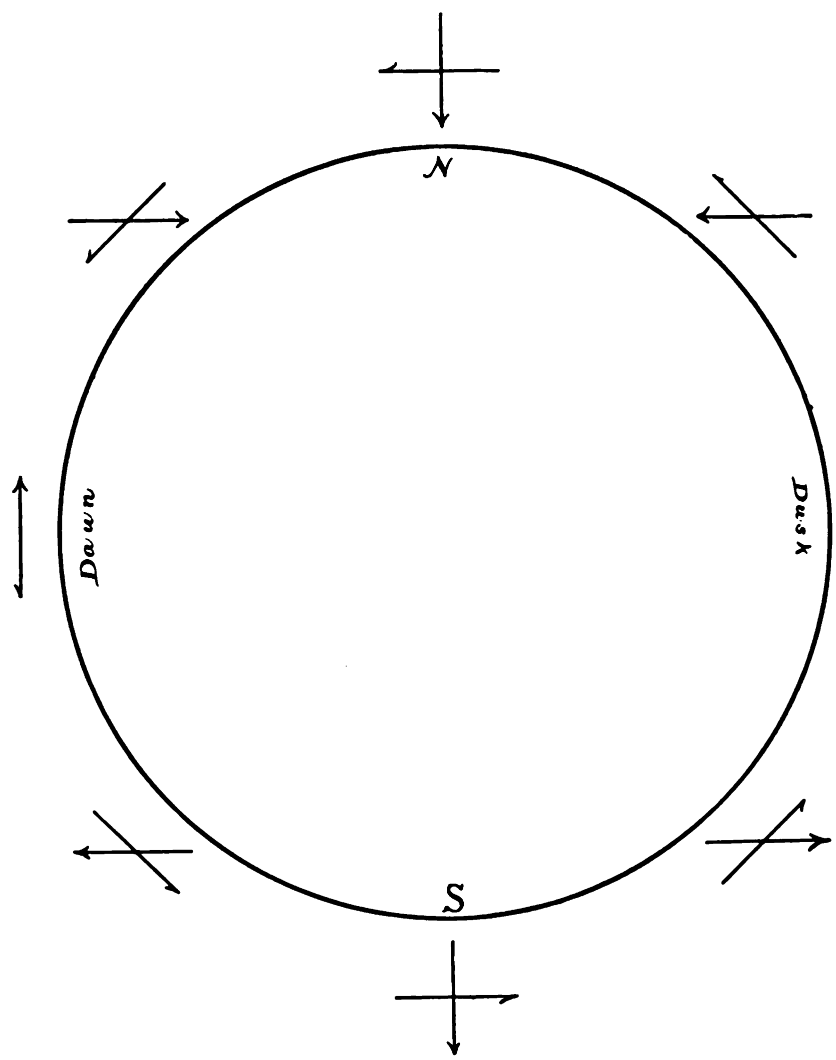
the greater solar intensity on the daylight hemisphere, to a minimum before dusk, and increases through the night. Its diurnal range, so far as the solar force is concerned, increases with latitude; but this is opposed by the waxing of the planetary force in the same direction.

It is evident that at the magnetic poles the needle can never be vertical, and that there is no point upon the planet's surface where the needle remains vertical all day. Also, that the points where the needle is momentarily vertical, are two, situated in the sunrise meridian near the poles.

If the planet rotate, and its axis of rotation, at any time, be oblique to the direction of the sun, the tendency of the solar atmosphere, at that time, is to induce magnetism in the planet. Whatever the inclination of the axis to the sun's direction, whether positive, zero, or negative, such magnetism as fills the boreal regions of the earth is still induced in the northern regions of the planet, as determined by considering its rotation from west to east; and the opposite magnetism is induced in the southern regions. Because of this obliquity, the tendency of the solar atmosphere, at any instant, is to so magnetize the planet that its magnetic poles err from the rotation poles. If the planet were composed of soft iron, the magnetic poles would complete a revolution, with respect to the planet, about the rotation poles from east to west in each single day. But, if the substance be such that the inertia of magnetism is great, the magnetic poles, wherever stationed at any time, remain virtually fixed, not only through one but through many days, since the effect of the planet's rotation is mainly to produce a reciprocating and not a progressive motion of the poles.

Let us consider the magnetic poles of the planet to be coincident with its rotation poles, as we examine the effect of the solar stream upon magnetized needles distributed over the surface of the planet, since the nature of the variations thus caused are of the same kind, whether the magnetic axis be coincident with the axis of rotation or not. As the planet performs its circuit round the sun, the inclination of its axis to the sun's direction continually changes. Let us examine the effects when the

north pole most inclines toward the sun, and when it most is turned away, that is, at the summer and winter solstices of the northern hemisphere. The variations of the equinoxes have already been discussed. At other



DIURNAL VARIATIONS OF THE DIPPING NEEDLE.

points of the orbit, the several variations are intermediate in character, and need not here be treated.

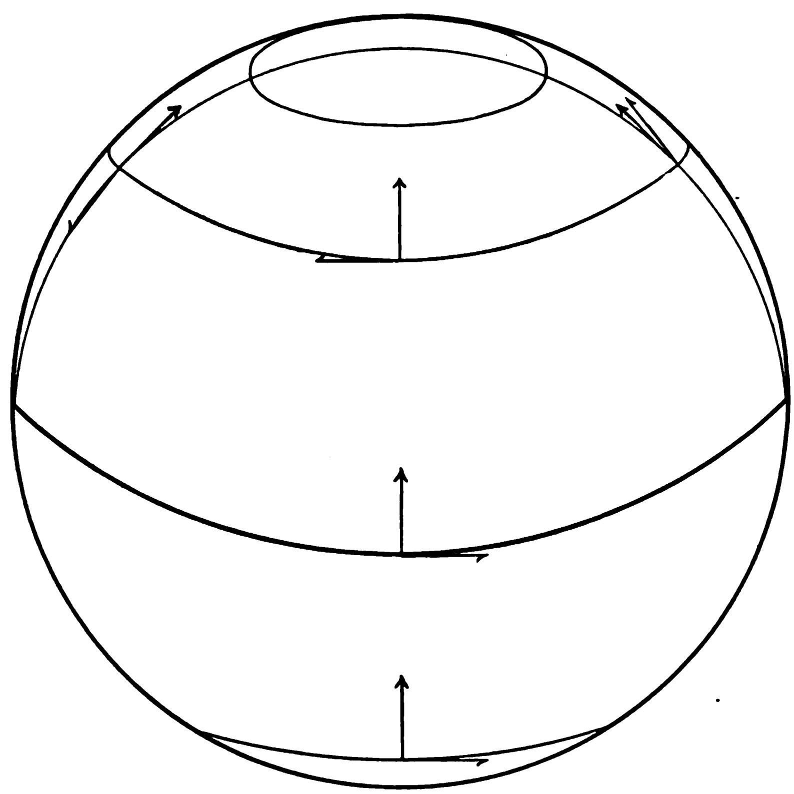
At sunrise of a summer day in the northern hemisphere the effect of

the planet's magnetism is to direct the needle north, but the effect of the solar stream is to direct it southeast; hence the needle is deflected to the east, whereas at the equinoxes it is not so deflected. The easterly deflection of the needle continues into the forenoon until the position is reached,—readily calculated, or determined by graphical construction,—where the solar stream tends to direct the needle due south. From this point till noon the needle is deflected westerly, as at the equinoxes, and so it continues to be until a point in the afternoon is reached where the effect of the solar stream is to direct the needle due north. Thence till sunset the needle is deflected easterly again. It therefore happens that the nature of the daylight variation of the needle's direction remains the same at the summer solstice as at the equinoxes, the needle swinging westwardly from a point in the forenoon to a maximum in the neighborhood of midday, and thence eastwardly till nightfall; but the range of the variation is greater in the summer than at the equinoxes, because in the former season the needle is deflected eastwardly at the beginning and end of the day, whereas in the latter seasons it is not. For the same reason, the nocturnal range of eastern deflection is diminished. We have, indeed, superimposed upon the equinoctial effect of a westerly deflection all day with a maximum at noon and zero values at sunrise and sunset, and an easterly deflection all night with a maximum at midnight and zero values at dusk and dawn, the summer solstice effect of an easterly deflection day and night with maximum values at morn and eve, and zero values at noon and midnight.

There is, however, a slighter contrary effect overbalanced by the preceding. At noon in summer the needle is nearer to the centre line of the interrupted solar beam than it is at the equinoctial noon. Hence the westerly deflection is a little less. At midnight the easterly deflection is a little more.

In the southern hemisphere, at the beginning and end of day, the needle is deflected eastward, whereas at the equinoxes it is not; hence the diurnal range of variation of the needle is diminished, although the easterly deflection at noon is also somewhat increased by the approach of the needle to the apparent rim of the planet as viewed from the sun.

The nocturnal range of variation is increased. The southern hemisphere by day is affected in the same manner as the northern hemisphere by night, and the southern hemisphere by night as the northern by day; but it must always be remembered that the solar stream is more powerfully electrified before it has come in contact with the planet's atmosphere than when it has passed into the region of night, and, therefore, more



VARIATIONS IN DECLINATION OF MAGNETIZED NEEDLES AT THE SUMMER SOLSTICE.

effective upon the needles under the sun than upon the needles under the stars.

At daybreak on the equator the tendency of the solar stream is to direct the needle east of south by the angle that the equator makes with the ecliptic. The deflection is easterly. At sunset the tendency is to set the needle east of north by the same angle. The deflection is here

easterly also. At noon the deflection is easterly because the needle is nearer to the south point of the apparent disc of the planet. Hence the deflection from the magnetic meridian is easterly all day, but greatest in the morning and evening, where the intensity of the force of the solar stream is vastly more than at noon time. So the needle swings westerly through the forenoon and easterly through the afternoon. At night, also, the deflection is easterly, least so at midnight and most at the end and the beginning, the needle again swinging westerly and easterly as before.

By day the equator partakes of the variation peculiar to the northern hemisphere, but the declination peculiar to the southern. By night it is the reverse.

Thus at the summer solstice, both in the northern hemisphere and the southern, and in the light and in the dark, every needle at every time is deflected more easterly than at the same daily time at the equinoxes. The easterly deflection of the northern night encroaches upon the westerly deflection of the day, and the easterly deflection of the southern day encroaches upon the westerly deflection of the night.

What is to be said of the planet at the winter solstice is easily deduced from what has been said. The range of declination variation in the northern day and southern night is less than at the equinoxes; in the northern night and southern day it is greater; the kind of variation in each of these quarters of the sphere is the same as at the equinoxes and the other solstice. For, over all the globe is thrown a tendency to westerly deflection, a maximum at sunrise and sunset, a minimum at midnight and at noon, so that the westerly deflection of the northern day and southern night encroaches upon the easterly deflection of the northern night and southern day.

Upon the equator the needle is deflected westerly all day and night, but the needle swings easterly from morn till noon, and westerly from noon till nightfall, partaking of the kind of variation of the southern day, and of the declination of the northern day. Through the night the needle again swings from west to east, and then from east to west.

If the planet be attended by satellites, these become magnetized by the solar stream, and affect the needles upon the planet's surface. The disturbance caused by the satellites in the sun's outflying atmosphere also affects the needles. Thus is instituted a peculiar variation of the magnetic elements, depending upon the rates of rotation and the relative motions and positions of the planet and its attendant orbs.

The annual variations are these :

As the planet sweeps from summer solstice to winter, the daylight range of declination variation in the northern hemisphere diminishes. So does it in the southern hemisphere at night. This range increases in the remaining quadrants. From winter to summer the range in the northern day and southern night increases; in the northern night and southern day it wanes.

Since the tipping of the northern pole of the planet toward the sun increases the easterly deflection everywhere upon the planet, and the tipping of the southern pole toward the sun causes a universal westerly deflection, it happens that, as the planet passes from summer to winter solstice, the mean diurnal declination from the magnetic meridian, at any part of the planet, varies from east to west, and, as the planet passes from winter to summer solstice, the mean diurnal declination varies from west to east. The maximum east diurnal declination occurs at the summer solstice, and the maximum west diurnal declination occurs at the winter solstice.

At the equinoxes, the minimum horizontal force is induced to the morning meridian half way betwixt midnight and noon, because, there, the solar stream directly opposes the planet's magnetism; and, moreover, it is induced to a parallel circle nearer to noon, by the overhanging ring of greatest intensity in the tangential zone. Hence it occurs between these two. And the maximum horizontal force, for a similar reason, occurs between the same two circles in the afternoon. Now, as the planet moves from vernal equinox, the ring of greatest intensity retreats from noon in northern latitudes, and the line whereon the solar stream directly opposes the planet's magnetism in the morning, and directly conspires with it in

the evening, approaches noon. Accordingly, the maximum and minimum become more decided, and the diurnal range increased, in any northern latitude, until the ring and the line described have in that latitude reached intersection. When they have passed, and separate again, the range diminishes to summer solstice. But the times of maximum and minimum are little changed. From solstice to autumnal equinox, the variations are reversed.

But, in the southern hemisphere, the ring of greatest intensity, and the line whereon the needles are directed normally to the solar rays, do not approach, but separate more widely, the former moving toward the noon, and the latter toward the midnight. When they have become sufficiently disparted, they no longer conspire to produce one minimum and one maximum, but cause a lesser minimum to appear in the later night, and a lesser maximum in the early night, while the daylight points are less distinguished than in the northern day, and nearer to the noon. Opposite changes attend the progress of the planet from summer solstice to the equinox.

From autumnal equinox to vernal, the northern variations in horizontal force are like the southern in the other portion of the year, the minimum and maximum each dividing into two, which coalesce again; and the southern variations are like those of northern summer.

The intensity of the planet's magnetism, and, therefore, of the mean diurnal horizontal and vertical components, continually changes, being greatest when the axis of rotation is perpendicular to the solar rays, and least when this axis is most oblique to the solar rays. Hence there are two maxima at the equinoxes, and two minima at the solstices.

The range of these annual variations increases with the inclination of the planet's equatorial plane to the plane of the orbit. They are independent of the shape of the orbit, and of the longitude of perihelion with respect to the equinoxes.

The annual variations on account of the eccentricity of the orbit, the longitude of perihelion with respect to the equinoxes, and the longitude of the nodes of the sun's equatorial plane, are these :

On account of the eccentricity, the intensity of the planet's magnetism, and, therefore, of the mean diurnal horizontal and vertical components, continually changes, having one maximum near perihelion and one minimum near aphelion. Although this magnetism is coerced with comparative slowness, yet the planet is for many days nearer the sun than its mean distance, and for many days farther than its mean distance ; the daily effects in each case are cumulative. The maximum occurs shortly after perihelion passage, and the minimum shortly after aphelion passage. This function of variation is superimposed upon that due to obliquity of the ecliptic, according to the longitude of perihelion. The range of this variation increases with the eccentricity.

On account of the rotation and consequent oblateness of the sun's nucleus, its atmosphere, if not homogeneous, must be symmetrical with respect to its equatorial plane. If, as seems from the appearance of the corona and zodiacal light, the solar atmosphere is densest in this plane, its magnetic effects must there be greatest, too. Hence, the intensity of the magnetism of the planet, on this account, continually changes, having two maxima at the nodes of the sun's equatorial plane, and two minima where the planet has removed furthest therefrom. This function of variation is superimposed upon the others according to the longitude of the nodes of the sun's equatorial plane. The range of this variation increases with the inclination of the sun's equatorial plane to the plane of the orbit, with the extent of the orbit, and with the rate of variation in electrical intensity of the sun's atmosphere.

The intensity of the direct action of the solar stream upon the magnetized needles, is, on account of the eccentricity, greatest exactly at perihelion, and least exactly at aphelion ; and, on account of the inclination of the sun's equatorial plane, if the electrical intensity of the solar atmosphere varies as described, it is greatest at the nodes. With this intensity increase and diminish the diurnal ranges of variation in declination, horizontal force, and inclination. These annual variations are superimposed upon those due to inclination of the planet's axis, according to the longitudes of perihelion, and of the nodes of the sun's equatorial plane.

It is unlikely that the outflow of the solar atmosphere is perfectly uniform and steady. It must be continually varying, through small ranges, in velocity and density; hence, in the quantity of electricity carried past the planet in each unit time. The consequent small and rapid fluctuations in magnetizing power of the solar stream must be virtually ineffective in altering the fixed magnetism of the planet, while they are instantaneously appreciated by the magnetized needles.

The effect of solar fluctuations upon the needles is this : As a wave of greater electrical intensity than the normal sweeps by the planet, the needles in the northern day and southern night swing toward the west from their normal directions for each place and time, and then back to their normal directions. In the northern night and southern day, the needles swing eastwardly and back. The inclination of the dipping needle increases between midnight and noon through the region of morning, and then decreases again to its normal inclination. In the region of evening from noon to midnight, the swing of the needles is toward the horizontal and then back. As a wave of less electrical intensity than the normal sweeps by, all the needles swing in the direction opposite to that described. The duration of the oscillation is the time required for the solar wave to pass the needle. The amplitude varies with the difference in electrical intensity from the normal.

The diurnal and annual variations of the irregular vibrations of magnetized needles, and the variations due to latitude and to the superior intensity of solar force upon the daylight side, correspond exactly with the variations of the regular vibrations, and may be thus epitomized:

Since the lever-arm factor of the magnetic moment upon any horizon-needle varies independently of the state of the solar stream, the total deflection from the planet's true magnetic meridian, at any time and place, varies simply as the intensity of the solar stream. Hence, at the passage of a solar wave of greater electrical intensity than the normal, the north end of the needle moves rapidly forth from its normal position for that place and time, in the same direction in which it is already slowly moving on account of the regular diurnal variation, and completes its oscillation

by swinging back to the normal position, as the solar wave departs. But, at the passage of a solar depression of electrical intensity, the oscillation occurs upon the opposite side. In either case, the amplitude of the irregular vibration varies directly as the normal deflection of the needle at that time and place from the planet's true magnetic meridian.

The irregular vibrations in horizontal force and inclination obey the same law, appropriately worded.

Fluctuations in the solar stream of brief duration in comparison with the length of a day, do not alter the range of daily variations, although the fluctuations may continue all day long. But a change in the strength of the solar current lasting longer than a day, increases the daily range of variations, if the strength of the current be increased, and decreases the range, if the current be diminished, the variation in the current acting more effectively upon the needles than upon the inert magnetism of the planet. For the same reason, if solar activity be increased for longer than a year, the annual variations increase also ; or diminish, if solar activity be diminished for so long a time. So the amplitude of vibrations, and the diurnal range of variations, record the degree of the sun's activity ; not instantaneously, for the electricity is carried by convection, not conduction ; but after the lapse of considerable time,—perhaps a week in case of the earth, according to the estimates already made.

There remains to be discussed the variation of the magnetic axis and meridians.

If, at the summer solstice, the relative direction of the solar ray with respect to the planet's surface upon the equator at dawn, whatever the velocities of transmission and rotation may be, be platted, it will be found that the magnetism thereby induced in the planet is such as causes the northern magnetic pole to lie upon the great circle whose plane passes through the sun's centre, at a point beyond the northern rotation pole, as measured from the sun, but not so far as to the arctic circle. The northern magnetic pole that results from the combined influence of the solar rays upon every portion of the planet's surface that is passing from midnight to noon, occupies a position similarly described. The combined influence

of the solar rays upon all those portions of the planet's surface that are passing from noon to midnight, is to induce an opposite, but less intense, magnetism, whose northern pole is of the opposite kind of magnetism, and is situated toward the sun from the northern rotation pole, on the great circle passing through the sun, but not so far from the rotation pole as is the arctic circle. The resultant of these two influences, at any time, tends to place the northern magnetic pole in a position such as first described, and to endow it with such magnetism as affects the boreal regions of the earth, Of the southern magnetic pole, which is antipodal, the like is to be said.

At the winter solstice, the northern magnetic pole is induced toward the sun from the rotation pole, and the southern from the sun, both in the great circle whose plane contains the sun's centre.

At the equinoxes, the magnetic poles tend to coincide with the rotation poles.

If the planet were composed of soft iron, the magnetic poles would daily perform a complete revolution from east to west about the rotation poles, and the annual variation would be this : As the planet passes from summer solstice to autumnal equinox, the amplitude of the diurnal sweep of the magnetic poles would dwindle from a maximum to nothing. Thence to winter solstice the amplitude would increase to a maximum again, and thence to summer, suffer another diminution and increase. That is, the magnetic poles would relatively to the planet's surface, sweep inwardly along a spiral to the rotation poles, and thence outwardly along a similar spiral, performing the double change in each half year.

But, if the substance of the planet be such that the inertia of its magnetism is great, such disposition as at any time exists reluctantly suffers change. Internal shocks and quakings tend to fix the magnetic axis, as does the distribution of magnetic substance. As the tendency of the solar stream is to induce eccentric magnetism throughout the year, except at equinoctial points, the planet is likely to be eccentrically magnetized.

However strongly magnetized a body may be, and however great the inertia of its magnetism, its polarity and intensity are slowly coerced to

If a body of great inertia be free to move in the circumference of a circle, and if it be solicited by an attracting force that acts in a right line with intensity varying as a function of the distance, and if this force emanate from a point that moves rapidly in the circumference of the same or a concentric circle, at a uniform rate and in a constant direction ; then the body of great inertia is caused to move slowly in the same circular direction as that traveled by the force. For, when the force is in conjunction with the body, its effect is null. As the seat of force moves rapidly onward, it slowly draws the body after it in the same circular direction, until the force comes into opposition, which happens after the force has traveled through more than a semi-circumference ; and there its effect is null again. In process from opposition to conjunction again, the force solicits the body in the opposite direction ; and, whether the body be moved in this direction, or be brought to rest, or be merely retarded in its original progress, the force passes from opposition to conjunction in shorter time than that it has required to pass from conjunction to opposition. So, continually, each successive interval during which the body is urged in the direction traveled by the force, is longer than each interval during which the body is urged in the opposite direction. Hence, the body is caused to oscillate back and forth, and at the same time to progress constantly in the circular direction traveled by the force.

Now, when the north magnetic pole, in the summer portion of the year, is upon the midnight meridian, the effect of the magnetic field that compasses the planet, to produce a movement of the pole in longitude, is zero ; but, as the pole is carried on toward noon, it is still continually urged toward midnight, that is, from east to west. Wherefore, a slight movement takes place in this direction, and the pole crosses the noon meridian after a transit that has required more time than half a day. Thence to midnight, the pole is urged eastward, that is, in the direction of rotation, and, consequently, makes the passage in less than half a day. Hence the pole is urged westwardly a longer time each day than it is urged eastwardly. The same is to be said of the southern pole, with reversal of meridians. The same is to be said of both poles in the winter portion of the year, with reversal of meridians. So, daily, and yearly,

portion of the surface acts for itself according to the quantity and shape of the magnetic material there imbedded. Hence the magnetic meridians and axis are thrown into flexures. It is probable that each planet, on account of the disposition of its materials, has a propensity to become magnetized about a particular diameter as axis. This mars the uniformity of the secular change, alternately accelerating and retarding it.

These are the main deductions from the theory. They seem to agree essentially with the observed facts.*

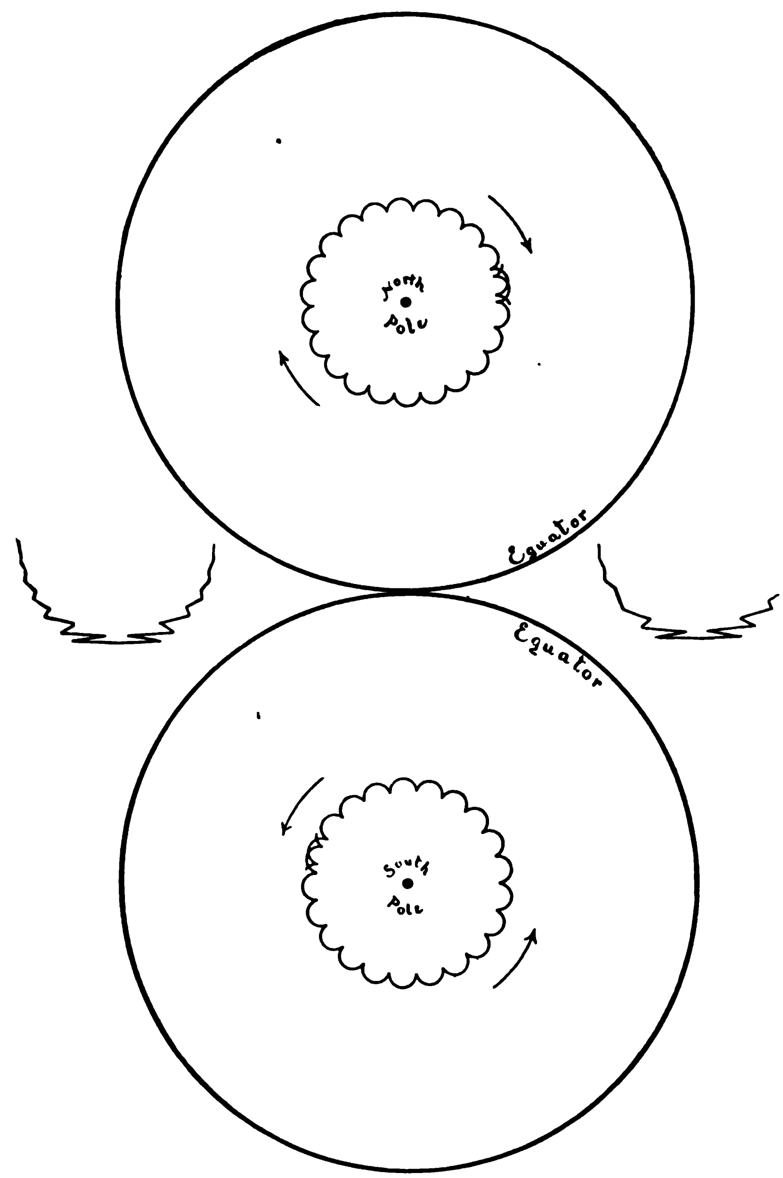
How the planet acquires magnetism is easily explained. Its non-magnetic material constitutes a revolving frame work. First, let the axis be perpendicular to the solar rays, and suppose that the only magnetic material is a single soft iron bar at the equator, directed north and south. As it sweeps through the morning region, this bar becomes polarized so that its northern end is charged with the magnetism of the earth's boreal regions. The polarization diminishes till noon, when it vanishes. Immediately after, polarization of the opposite kind commences, and till nightfall it increases; that is, the northern end becomes charged with the magnetism of the earth's austral regions. This diminishes till midnight, then vanishing. From midnight till daybreak the first-mentioned kind of polarization recommences, and increases to a maximum. The polarization is stronger at every instant from midnight till noon than in the diametrically opposite instant between noon and midnight. Hence the mean diurnal polarization is of the first kind.

The intensity of the mean diurnal polarization increases with the rate of rotation, and decreases as the axis of rotation departs from perpendicularity to the solar rays.

If one of the spherical layers of the planet's crust be filled with soft iron, either continuous or in separated masses, the polarity at all points on the surface, from the equator nearly to the rotation poles, changes ends during each rotation, as in the case of a single bar.

* *Encyc. Brit.*; Art., *Meteorology*: *Amer. Cyc.*; Art., *Magnetism*: *A Treatise on Magnetism*, by Humphrey Lloyd, D.D., D.C.L.: etc., etc.

Now consider a single bar placed as first described, but consisting of steel, or magnetite, or other material at once strongly magnetic and



SECULAR MOVEMENT OF THE MAGNETIC POLES.

possessing great magnetic inertia. As it sweeps through morning, a slight polarity is induced, of the kind peculiar to the morning. A portion

of this is removed by the opposite, but weaker, influence of the solar stream, as it flows by the side of the planet moving in its own direction, that is, in the region of evening. So the magnetic bar passes midnight retaining a little of the kind of polarity induced in the morning. This polarity is daily increased, more and more slowly, until its potential is algebraically half way between those due to the morning and evening portions of the solar stream, respectively. Then it becomes permanent.

Let similar bars, or irregular masses of magnetic material of great inertia, be thickly distributed through the crust. The kind of permanent polarity induced in each mass is the same from equator to poles. The intensity of the permanent magnetism induced in each individual mass, directly by the solar stream, diminishes from equator to the poles. But the mutual influence of the magnetized masses places the general magnetic poles in the planet's polar regions. Since this influence is greatest at the equator, and least at the poles, there is not a strong tendency to fix the general poles definitely in position. The polarity at every part of the surface remains the same in kind during a complete rotation. All this is true if the magnetic material exist in a continuous spherical sheet.

The intensity of the planet's magnetism declines as its rotation axis departs from perpendicularity to the solar rays. In the case of a planet like Uranus, of long period, aud whose axis is nearly coincident with its orbital plane, the variation in magnetic intensity is considerable.

The swifter a planet whirls, the more effective is the morning portion of the solar stream in polarizing the magnetic masses so that their northern poles shall be charged with the magnetism of the earth's boreal regions, and the less effective is the evening branch of the solar stream in reversing this polarity. Hence the magnetism of the planets, diminishing as the distance from the sun is more, increases with the velocity of rotation.

The nature of the magnetic field surrounding the planet is this :

First, there is the primary field, created by the interruption of the solar stream. Its potential increases symmetrically outward from the axis

at morn and eve, then it is to be inferred that the globe contains no magnetic material. If the needles in the northern hemisphere complete a rotation in direction of a watch's hands, pointing north at daybreak and south at nightfall, and the southern needles perform a rotation in opposite direction from a like pointing at morning and dusk, then it is to be inferred that the globe is largely composed of magnetic material of little inertia. If the direction of the needles remain nearly fixed, it is to be inferred that the planet is not an electro-magnet, with or without a susceptible magnetic core, but that it is a permanent magnet, containing a large quantity of magnetic material of great inertia.

This material is likely to be irregularly distributed, and the symmetry of the induced field thereby disturbed. If the deviations from symmetry be, in general, slight and gradual, this indicates either that the material is somewhat evenly spread, or that it is deeply buried in the crust. Wherever the deviations are abrupt, a magnetic mass exists near the surface. If the intensity be greater throughout a vast region than that pertaining to a symmetrical field, culminating at a point, this indicates that the magnetic material lies eccentrically in the crust. The measurement of the mean annual total force, and its direction, at every point of the planet's surface, does not suffice to make known the arrangement of magnetic material beneath; for a myriad various arrangements give rise to the same indications; but a supplemental series of measurements, taken above or below the surface, renders the problem determinate.

The secular movement of polarity occurs in each individual mass, and inevitably changes slowly the intensity of the neighboring field.

The existence of a mass of soft iron, naturally or artificially deposited, is made known by its effect upon the irregular and the diurnal variations of the needle, as well as upon the declination and dip. For, the neighboring field being sensitive and opposite to the primary, the variations of the needle diminish upon approach, until they disappear; and, then upon nearer approach, they increase in the opposite direction.

The theory indicates that the causes of the annual, diurnal and irregular variations have reference to the planet's axis of rotation, and not

to the magnetic axis. But the permanent declination affects the magnetic moment, and, by this means, the amplitude of the several variations, sometimes even changing their direction. For instance, if the declination be east, then, at dawn, the deflection of the horizontal needle from the magnetic meridian, as deduced when the declination is zero, is always increased when that deflection is easterly, and always diminished when that deflection is westerly. In consequence, the deflection of the needle is not easterly half the year, and westerly the other half, but is easterly for more than half the year; and, if the declination be greater than the inclination of the equatorial plane to the plane of the orbit, the easterly deflection continues throughout the year. At sunset, westerly deflections are increased, and easterly deflections diminished, the latter sometimes becoming westerly. At noon and midnight, the deflections are decreased, whether they be easterly or westerly.

One effect of the east declination is to increase the range of variation in the forenoon and early part of night in the northern hemisphere throughout the year, and diminish it in the afternoon and later night. In the southern hemisphere the reverse happens.

A west declination reverses all these effects upon the horizontal needle.

East and west declinations concur in reducing the variation of inclination at dawn and dusk, and in increasing it at noon and midnight.

The effects upon the horizontal and total forces are, likewise, easily deduced.

In this manner a complete account of the annual, diurnal and irregular variations of all the magnetic elements at any station, whatever its declination, can be deduced directly from the theory. The detailed account of previous pages applies to the line of no declination.

The true magnetic meridian at any place, due to the planet's permanent magnetism, is not to be found by laying off the mean declination from the astronomical meridian. For, the daytime deflection is greater than the opposing night time deflection, on account of the greater potency of the solar stream upon the daylight side; and the morning deflection,

on account of declination, is greater than the opposing deflection of nightfall. Theoretically, the needle indicates the true magnetic meridian whenever the effect of the solar stream coincides in direction with, or directly opposes, the planet's permanent magnetism ; that is, twice daily when the horizontal needle is perpendicular to the solar rays. Another method for finding the true meridian depends upon the principle already stated, that the amplitude of the irregular oscillations of the needle varies directly as the normal deviation from the true magnetic meridian. If, in the durance of a magnetic storm, the oscillations dwindle, cease, and then begin again, the direction of the needle at the instant when oscillations vanish, is that of the true magnetic meridian.

The superior potency of the solar stream upon the daylight side of the planet is never to be neglected. All the indications establish its existence. This is further to be emphasized by the consideration that the rays of the solar stream are not elements of a cylinder tangent to the planet, but of a double conoid or spindle. Thus the extent of tangency between the solar stream and the planet's atmosphere, is increased, causing the least exhausted, and, therefore, most effective, section of the stream to be on the daylight side, much nearer the sun than the section whose plane passes through the planet's centre.

Far slighter and less effective is the difference in potency between the morning and evening sides of the planet, due to its rotation.

An important modification of the theory is due to aberration. As the planet sweeps through space, the solar stream encounters it not from the direction of the sun, but from a direction forward of that luminary. The effect upon magnetic phenomena is simply to shift them all a little earlier in diurnal time, without disturbing the succession or importance of events. An annual variation in the amount of aberration exists ; very slight, for the reason that, as the velocity of the planet's motion increases from aphelion to perihelion, so does the velocity of the sun's atmosphere increase as the revolving body approaches the central orb. The effect upon the annual variations is equally simple. The planet's rotation axis

does not become perpendicular to the solar rays at the equinox, but at a point beyond, whose angular distance from the equinox is equal to the aberration. Neither is the axis most diverted from perpendicularity at the solstice, but at a point beyond, whose distance therefrom in angular measure is equal to the aberration. So the events are all belated in yearly time, while their order and importance are not disturbed.

The close correspondence between the observed positions in diurnal time of the various magnetic phenomena upon the earth, and the positions assigned directly from the theory, when aberration is neglected, shows that aberration is small,—certainly much less than an hour in time. From this it appears that the velocity of the solar atmosphere at the earth's orbit must be at least fourfold as great as that of the planet itself, or seventy miles per second, and is probably much greater. Since the irregular oscillations of the needle cease at the instant when the needle becomes perpendicular to the plane through the needle and the axis of the primary field, if this instant during a magnetic storm could be nearly fixed, the aberration, and the outflying velocity of the solar atmosphere, could as nearly be determined;—more nearly from the observations of many stations, taken on many occasions.

There is nothing in the theory to indicate that the sun is a magnetized body, or is surrounded by a magnetic field.

PLANETARY ELECTRICITY

THE outflying solar atmosphere, charged with positive electricity, produces upon the planets electrical effects as well as magnetic. If the period of rotation of a planet be synchronous with its period of revolution, so that the same face is ever presented to the sun, the electrical effects are these :

Where the charged solar atmosphere comes into tangency with the neutral planetary atmosphere, that is, around the ring that divides the region of eternal day from the hemisphere of darkness, a continual interchange of electricities takes place, accompanied by a faint glow visible to the dwellers of the night. The planet is surrounded by a halo. Since, as already explained, the region of tangency is a broad band reaching into the daylight portion and into the dark, and since the interchange of electricities is most vigorous at first touching, the halo surrounding the planet is intrinsically brighter on the daylight side of the sphere, although it is there actually more obscured.

The electricities of the planet are partially dissociated by induction. The negative kind is drawn to the neighborhood of that circle which severs the day from night, occupying a broad band reaching into the sunlit and starlit portions of the planet's surface, intenser on the daylight side than on the dark. The positive kind is repelled to the centres of day and night, but chiefly to the centre of the globe itself. No ground currents exist, for the conditions are constant, or, at least, change simply with fluctuations in the electrical intensity of the solar stream.

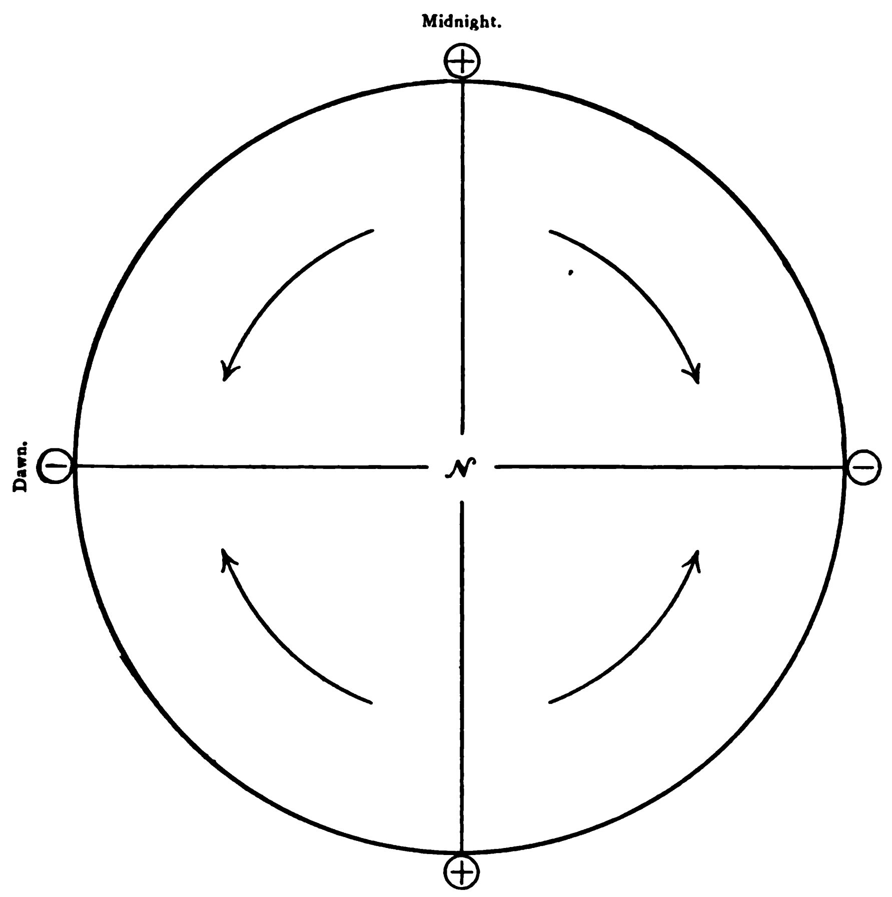
Through the planetary atmosphere continually passes positive electricity from the solar stream downward to the liquid and solid surface, at a rate governed by the conductivity and commotion of that atmosphere;

and upward flows an equal quantity of negative electricity to be swept away by the solar stream. The ratio of positive electricity to negative in the atmosphere increases with the altitude from its base to its outmost limits. The difference in potential between the solar stream and the planet's crust is greatest in the zone of tangency; here, also, they approach most nearly. Here, then, the gradient of electrical intensity is steepest; the differences in potential between concentric layers of the crust, between the crust and air, and between concentric layers of the air, are at their maxima. In this zone are, therefore, congregated the electrical phenomena; but, principally, a little sunward from the circle that bounds the day and night.

If the planet rotate, and the axis of rotation be normal to the plane of the orbit, the zone of tangency constantly passes through the rotation poles. Every point on the planet in a lower latitude sweeps through the zone of tangency twice during each rotation, and twice traverses the intervening spaces. Relatively to the planet, there flow two tides of negative electricity from east to west with a velocity equal to that of rotation, and two intervening tides of positive, or less negative, electricity in the same direction. If the globe were composed of copper, the negative wave crests would occupy nearly the meridians of sunrise and sunset, and the negative wave hollows, or positive crests, would occupy the noon and midnight meridians. This steady flow of electricity cannot fitly be termed a ground current, because its velocity is no greater than that of rotation, and its effect in producing a magnetic field is small. Upon a magnetized needle upon the planet's surface, sweeping from dawn to noon or from dusk to midnight, the effect is that of a stream of positive electricity passing under the needle from east to west; the effect during the transit of the intervening quadrants is that of a stream of negative electricity passing under the needle from east to west, or of a stream of positive electricity passing from west to east.

If now the globe were girdled with a copper wire, lying upon a circle of latitude, and grounded at various places, in this wire no current would be produced, although connecting portions of different potentials. For, being of the same material as the globe itself, it merely transmits the suc-

cessive waves at a velocity equal to that of the rotation. The quantity of electricity conveyed would be too small to be detected. A wire stretched north and south, although connecting different potentials, would convey no electricity whatever.



ELECTRIC TIDES IN METALLIC GLOBE.

If the planet be composed of a poor conducting substance, the crests of these flowing tides are thrown eastwardly all, the negative crests occurring after dawn and dusk, the positive crests in afternoon and past midnight.* The relative flow of the tides is, likewise, shifted eastward

* From this it is to be inferred that through submarine telegraphic cables artificial waves of negative electricity will flow more rapidly, and of positive electricity more slowly, in forenoon and the early part of night than in the other quadrants of the day, on account of the varying condensing powers of the electric tides.

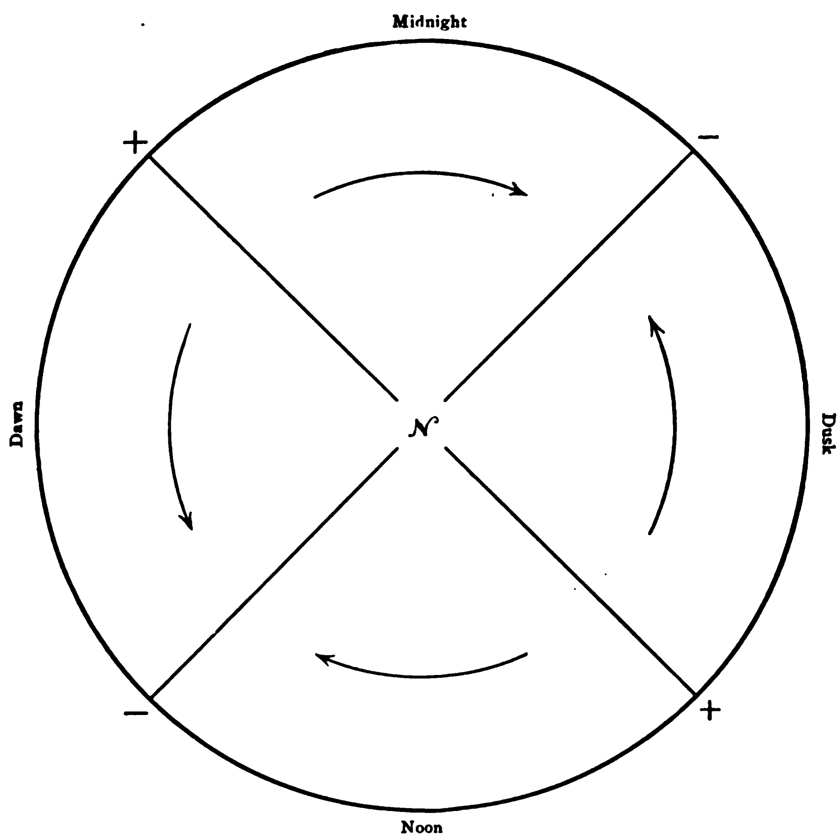
in position, remaining the same in velocity and direction. In the region of dawn, the effect upon a horizontal magnetized needle is to reinforce slightly the effect of the solar stream. In the region of dusk the flow of the tide opposes slightly, in effect, the flow of the solar stream. In the regions of noon and midnight the effect of the tidal flow is to increase slightly the magnetic effect of the planet itself. In the latter two regions the inclination of the dipping needle is slightly diminished ; in the former two it is slightly increased.

The belating of the electric tides depends upon the resistance of the planet's material, and not upon the velocity with which electricity can flow through that material. If the crests of the tides were occupying the cardinal meridians of noon, midnight, dusk, and dawn, the electro-motive force of induction would be zero, and not the least resistance could be overcome ; hence, even in a copper rotating sphere, the tides would be carried somewhat eastward of the cardinal meridians. Up to a certain limit, the deflection of the tidal crests increases the electro-motive force that urges the maximum charges back toward the cardinal meridians. As the resistance increases, the deflection increases, until the electro-motive force is sufficient to overcome the resistance. If the resistance be greater than the maximum electro-motive force developed by deflection, the electricities will be carried bodily around with the planet's surface, experiencing no tides, but simply an acceleration and a retardation as they approach and depart from the cardinal meridians.

If the planet be circled by a metallic wire, trending east and west, and grounded at intervals, the wire composed of better conducting material than the planet's crust, and perfectly insulated from the air, electric currents will be produced in that wire in this wise :

The portion of the wire extending from the meridian of dawn to the forenoon crest, finds at its eastern extremity a higher negative potential than at its western end ; moreover, the influence of the solar stream is to induce a higher negative potential at the western terminus. Hence a current of negative electricity flows westward through the wire, which is equivalent to an eastward flowing current of positive electricity. The portion of the wire reaching from noon to the afternoon crest, finds at its

eastern end a higher positive potential than at its western end ; moreover, the effect of the solar stream is to repel the positive electricity westward. Hence a current of positive electricity flows westward through the wire. The portion of the wire extending from the forenoon crest to the noon meridian, finds at its western end a higher negative potential than at its



ELECTRIC TIDES IN NON-METALLIC GLOBE

eastern end ; but the effect of the solar stream is to induce a higher negative potential at the western terminus. Hence the current instituted in the wire is feeble and ambiguous. Undoubtedly the differences of potential, that due to induction, and that actually existing in this octant, do not balance exactly, but cause a slight current to travel through the wire,—how strongly, and in which direction, to be determined by nicer

analysis than here we shall attempt. In like condition is the portion of wire that joins the afternoon crest with the meridian of dusk. What is said of any octant of the day, the same is to be said of the opposite octant of the night, if we remember only that all effects of the solar stream are somewhat stronger on the sunlit surface than in the region of nocturnal shade.

Less abrupt are the changes that take place in a limited wire swept round with the planet's rotation. While in the first octant, reckoned from dawn eastward, the current is strong and eastward in direction. As the eastern end traverses the second octant, the current grows less until it vanishes when the west end also enters the second octant. When the east end enters the third octant, a westward current begins, and this waxes in strength until the maximum is reached when both ends occur in the same octant. In like manner the current successively wanes, vanishes, changes direction, waxes and wanes again, throughout the day and night.

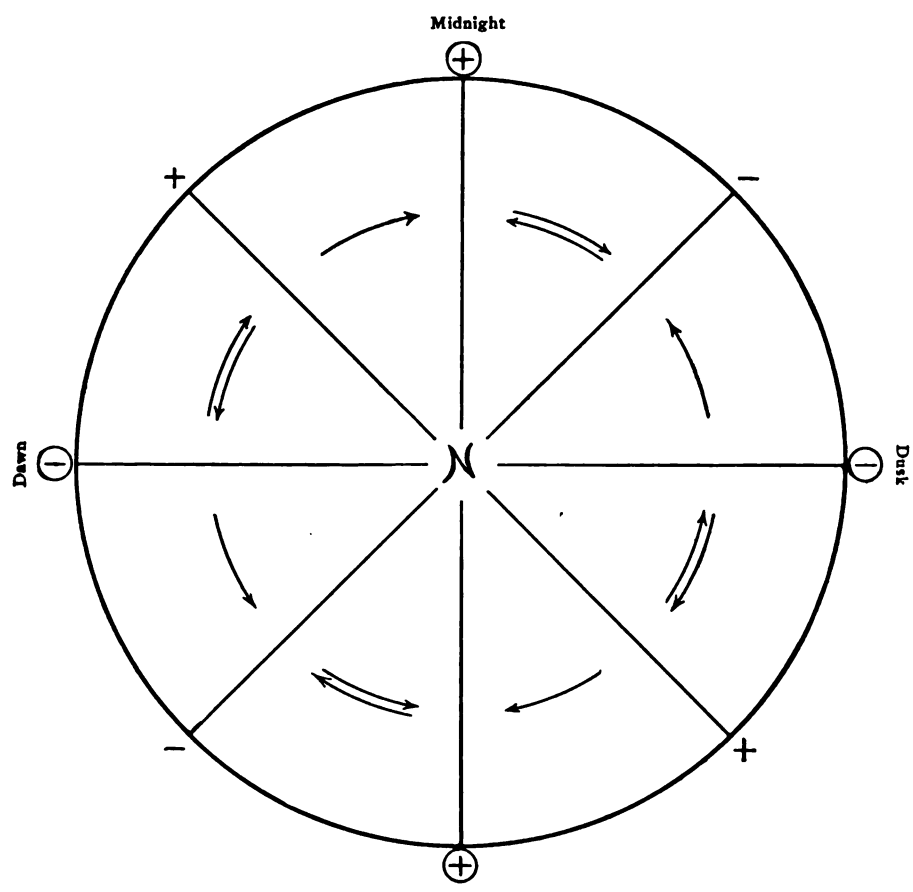
The longer the wire, the greater the electromotive force, until a length is reached that spans any of the odd octants; beyond this, the longer the wire, the less is the electromotive force. But through the same cycle of changes goes the current in the wire, whether it be short or long.

As the difference in potential between the negative and positive crests is a maximum at the equator, and dwindles to zero at the poles, so the electromotive force of the wire currents, spanning in all latitudes the same number of degrees, is greatest at the equator, decreases as the latitude increases, and becomes nothing at the poles.

Such should be the phenomena exhibited by the earth at its equinoxes.

If the axis of rotation be oblique to the orbital plane, the zone of tangency passes exactly through the poles at no time except at the epochs of the equinoxes. At the solstices it is farthest from the poles. At the summer solstice, in the northern hemisphere, the forenoon crest is earlier than at the equinoxes; that which follows dusk is later: the distance

between them, as measured through the day, is more; as measured through the night, it is less. This variation in position is least at the equator, increases with the latitude, and becomes a maximum at the polar circle, where the two negative crests coalesce on the midnight meridian. From this circle to the pole there is still but one tide, culminating at the midnight; but the difference in potential diminishes to the pole.



WIRE CURRENTS—FRICTIONAL ELECTRICITY

In the daytime of the northern hemisphere, the difference in potential between the negative crests and hollow is greater than at the equinoxes; in the night it is less. Hence the electromotive force, both in wire and crust, is more in the day and less in the night; but the resistance varies in the same way.

Of the southern hemisphere the reverse must be said. In the winter solstice the conditions are reversed.

If wires be stretched along the meridians, and in all other directions, in these currents will be established that likewise vary as the year goes round. To determine the direction and electromotive force of these, plat upon the globe the potentials that would exist if it were composed of the material of the wire, and over this plat the potentials that actually exist. From the difference in potential for any two points, as first found, subtract the difference in potential as lastly found; this difference indicates the direction and electromotive force of the consequent wire current.

So we have electric tides in the crust and electric currents in the wires. The wire current is a differential depending upon the relative resistances of the crust and wire.

The electricity is frictional; it escapes from an uninsulated wire. Yet in the octants of strong currents the tendency to escape is small; for the difference in potential in the wire is as great as in the ground, and the resistance less. So water, forced into a horizontal perforated tube, escapes; but not so in a vertical tube. If the wire at any place be doubled upon itself, the electricity will there rapidly escape; it is so with the current of water in a vertical tube flexed at some part. If the wire be coiled the electricity rapidly escapes in the coil and in its neighborhood.

Such are the effects in a sphere of homogeneous, poor-conducting material. If the substance of the planet be not homogeneous, the resistance will vary with place. It will be greater in water than in the overstretched wire; still greater will it be in moist sandstone and limerock; greater still in the dry metamorphic rocks, and most of all in masses crystalline. As the tide's flow is barred, it seeks out channels, through which it rushes impetuously, twice daily surging forth and back. Where large tracts of uniform resistance lie, the flow is steady and slow, retarded like ocean tides that come upon a wilderness of sea-grass. The flow in the wire is free and fast, like that of water in a smooth trough laid among

the grasses. Where a long reach of small resistance is abruptly terminated by an extensive dike of igneous rock, the onflowing electricity is heaped up like Fundy tides, and a wire stretched over the barrier is charged with a current of tremendous electromotive force.

A network of short insulated wires, lying in all directions and distributed over the planet, would serve to reveal the location of barriers and tidal ways, and, to some extent, the structure of the planet's crust.

THE magnetic field produced by the interruption of the sun's outflying atmosphere, is, as already explained, a spindle in shape, the axis directed toward the sun,* and the normal cross-sections circles. The magnetic potential is symmetrical about the axis, increasing, in each cross-section, from zero on that line to a maximum on the spindle's surface. The potential is somewhat greater sunward from the middle cross-section, or zone of tangency, than upon the farther side, because the electric potential of the solar stream is reduced by contact with the planet's atmosphere. In this primary field exists, as previously explained, a secondary induced field of greater permanent intensity near the planet's surface, but far less susceptible to changes of potential. For this reason the secondary field need not be regarded in the following discussion.

As wires upon the planet's surface are swept through the magnetic field, in them galvanic currents are induced, whose strength and direction can easily be deduced from the Amperian laws. A wire stretched along the equator at the equinox, is from daybreak to noon carried away from a westward flowing solar stream ; hence the induced current is from east to west. At noon the current vanishes. Thence to dusk the wire is carried toward an eastward flowing solar stream, and the induced current is still from east to west. Throughout the night, the flow in the wire is eastward, except that in the middle night it vanishes. The higher the latitude, the less is the east and west difference in potential of the magnetic field, until at the poles it vanishes. Hence the currents thus induced decrease from equator to poles.

* The effect of aberration is nelected for the sake of simplicity of description.

As the east and west wire in any latitude is carried around the magnetic field, its direction with respect to that of the nearest rays of the solar stream continually changes. This rotation of the wire induces currents therein that at all times coincide in direction with those already described ; but the intensity of these currents increases from equator to the poles, because it depends upon the mean magnetic potential where the rotation occurs. Thus, in a short wire stretched across either pole a current is induced by forced rotation in this wise : while one end of the wire is in the afternoon, and the other end in the latter part of the night, a current flows from afternoon to night ; while the wire reaches from the fore part of the night to forenoon, a current flows from night to day. With respect to the wire itself, the current changes direction whenever the double meridian of midnight and noon is passed.

So the currents produced by translation and rotation of the wires, flow westwardly all day, and eastwardly all night ; the flow is everywhere from the hemisphere of dusk to the hemisphere of dawn. The variation of the current in respect of latitude is the sum of the two opposite variations described. The variation in respect of longitude depends upon the rate of rotation and the variation in intensity of the magnetic field. Since the relative velocity of the solar stream with respect to the wires is greater at one part of the rotation than at the opposite, it follows that the intensity of the induced currents is less in the hemisphere of dusk than in the hemisphere of dawn.

These effects upon the wires traversing the magnetic spindle are the counterparts of the effects upon the magnetic needles already discussed ; but the induced currents are very feeble on account of the slow motion of the wires. At any instant the magnetic needle shows the total effect of that portion of the magnetic field where it may have place, independently of the velocity with which it has reached its position ; but the wire reveals only the differential of magnetic potential that has been traversed in a fraction of a second.

Similar galvanic currents are induced in the planet's crust ; but these are far more feeble than those of the wire, for equal cross-sections, and entirely ineffective upon magnetized needles. Their influence opposes that

of the solar stream in the forenoon and the fore part of the night, and reinforces it in the other quadrants.

At the solstices the induced east and west currents are at a minimum, because the planes of rotation at those points become most inclined to the solar rays.

In a north and south wire on the equator no current is induced at the equinoxes. In other latitudes feeble, but opposite, currents are simultaneously induced on account of the translation and rotation of the wire relatively to the solar rays. In the afternoon and fore part of the night the current flows north in the northern hemisphere and south in the southern on account of the wire's rotation, and oppositely on account of its translation; in the latter part of the night and in the forenoon the opposing currents are each reversed in both hemispheres. The current due to translation increases with the latitude to a maximum, and thence decreases to the poles. The current due to rotation increases uninterruptedly from the equator to the poles, where it becomes identical with the current before described. The variation of the current in a north and south wire is the algebraic sum of the two component variations just defined.

Wires lying in other than the cardinal directions possess currents that are resultants of those described. In the planet's crust similar but weaker currents, for equal cross-sectional areas, exist.

If wires be stretched vertically at various places upon the planet, each terminating aloft in a reservoir of great capacity, or in an over-hanging portion of the planet's crust, and below in a similar reservoir or in the planet's crust, feeble, but conspiring, galvanic currents will therein be induced by translation and rotation. As each wire is swept through the magnetic field from noon to midnight, the current climbs; it re-descends from midnight until noon. Meanwhile negative frictional electricity rises at dusk and dawn, falling at noon and midnight. The galvanic currents are a maximum at the equator and dwindle to nothing at the poles. Thus the three components of the current can be determined in a wire however directed and inclined.

All the regular galvanic currents are probably inappreciable. They

have no reference to the positions of the magnetic poles, or the declinations of the magnetic meridians.

From such a conflagration as the sun's the emanations cannot be tranquil and steady. Such violent outbursts as are perceived to issue from his sides, are propagated to the limits of his atmosphere in ever dwindling irregularities as they blend in the general flow. Every region of his atmosphere is momentarily changing in velocity and density, and the susceptible magnetic fields instantaneously respond. Upon the increase either of velocity or density in the neighboring portions of the solar stream, the contours of the magnetic spindle rush inward toward the axis, and new and stronger potentials issue from the sides; the gradient becomes steeper, the magnetism more intense. As the velocity or density diminishes, the magnetic potentials retreat outward; fewer remain, and these are more widely separated. The intensity wanes and the gradient loses its steepness. As these magnetic potentials rush forward and backward across the needles and the wires, the needles are agitated,—sometimes violently,—and the wires are filled with currents surging to and fro.

The quick transition of potentials caused by the sweeping by of electric clouds in the ethereal stream, renders the irregular currents vastly more powerful than the regular currents induced by the planet's slow rotation. Their indications are correspondent and synchronous with those of the magnetized needles, but not always varying alike in intensity, because the magnetic moment is often very different for the needle and the wire. The maximum currents are induced in the zone of tangency, and the minimum on the axis of this zone.

In an east and west wire upon any latitude, at the equinoxes, the minimum currents are at noon and midnight, the maximum at dusk and dawn. The intensity increases with the latitude upon all meridians except the cardinal four. From noon to midnight, the direction of the current is from east to west, while the electric intensity of the solar stream is waxing; while this intensity is waning, the direction is opposite. The reverse is to be said of the hemisphere of dawn.

Thus, while the solar stream is waxing in strength, the regular currents oppose the irregular in the forenoon and early night, and reinforce them in the remaining quadrants. The reverse happens while the solar stream is waning in its strength.

In a north and south wire no currents are induced at the equator. In every other latitude currents are induced that, on account of the wire's direction relatively to the solar rays, diminish from the noon and midnight meridians to dusk and dawn, but, on account of the varying intensity of the magnetic field, increase from noon and midnight to the meridians of dawn and dusk. The currents increase in vigor with the latitude in all meridians except those of dawn and dusk.

Thus, in general, the strength of all irregular currents increases from the equator to the poles.

The direction of the meridional current is northward in the northern night and southern day, and southward in the northern day and southern night, when the intensity of the solar stream increases: all these currents are reversed when the solar potential wanes.

In general, the flow of all irregular currents is from the centre of night to the centre of day when the solar stream increases; and opposite, when the solar stream declines.

The annual variations are easily deduced from the principle just stated. The east and west currents decline from equinox to solstice. The north and south currents increase from vernal equinox to summer solstice, in the northern night and southern day, and diminish in the other two quadrants. Thence to the autumnal equinox, the currents gradually return to their normal values. From this point to winter solstice, the increase takes place in the northern day and southern night, and the decrease in the northern night and southern day. The currents return again to the normal state, from winter solstice to vernal equinox. Away from the equinoxes, the north and south currents no longer cease to flow in the meridians of dusk and dawn, but reach quiescence when they pass a line described as follows: Draw a tangent cone at each latitude, and mark the points where the elements perpendicular to the

solar rays, touch the planet; the curve through these points is the line of no current. At the solstices the line of no current does not enter the tropics.

The strength of a current lying in any direction, due to a certain disturbance, is a function of its distance from the axis of the magnetic spindle multiplied by the cosine of the angle it makes with the axis. The maximum currents are parallel to the axis and in the zone of tangency.

The nature of the correspondence between the indications of the wire and of the needle at any place, is easily deduced. For instance, the magnetic poles and meridians being coincident with the astronomical, at noon in the northern hemisphere the needle moves westward and a current flows southward, as the intensity of the solar stream increases; the opposite motion and flow occur simultaneously while the solar stream is losing strength. At dawn the needle merely dips, and the galvanic flow is eastward, as the electric cloud approaches. North of the equator, at dusk in the summer solstice, the needle swings eastward, and the current flows from southeast to northwest, making an angle with the circle of latitude equal to the angle of the ecliptic; this at the approach of the ethereal cloud, the reverse as the cloud departs.

The causes of these perturbations, like those of the regular variations, have no reference to the eccentricity of the magnetic poles and the declination of the compass. Yet, so far as the needles are concerned, the permanent declination affects the perturbations in this much, that it changes the magnetic moment, which alters the amount of deflection, and sometimes reverses its direction. For each station an ephemeris of the effects of disturbances upon the needle can be constructed, as heretofore explained, and the nature of the correspondence with the currents thence deduced.

Similar galvanic currents are induced in the planet's crust; but these are comparatively weak. As they are always opposite in effect to that of the changes in the magnetic field which produce them, but are at the same

time below the magnetized needles, the influence of the ground currents upon the needles is always in the same direction as that of the changes in the magnetic field. Their existence does not, indeed, augment the influence upon the needles, for they can do no more than return the force they have extracted from the field, and may do less. The current in the globe, like that in the wires, is merely a surging from night to day, as the energy of the solar stream increases, and an opposite surging while that energy continues to wane.

The wire currents are not derived from the planet's crust, but are co-effects with the ground currents and the needle's vibrations, of the changes occurring in the magnetic field. They are stronger in overground wires than in subsea cables, because the former occupy a free field, and the latter occur in a magnetic field whose changes are weakened by the currents induced in the crust itself. If the wire currents were derivatives of the ground currents, they would be stronger in the more conductive and better insulated cables than in aerial lines. Again, suppose one of two parallel wires to be grounded at both ends, and the other to terminate in reservoirs insulated from the planet's crust. Now, if ground currents were the cause of wire currents, the flows in the parallel wires would be opposite in direction; but, if changes in the solar magnetic field be the cause of the currents, the flows in both wires will be the same in direction.

The indications of the wires would be strengthened by coiling them at intervals about bundles of soft iron rods. One such helix, mounted so as to be capable of rotation in any plane, would probably furnish through a galvanometer indications of the variations in the magnetic field. If not, a battery of such helices might so serve.

WE are led to the conclusion that all the magnetic manifestations in the planet are due, not to galvanic currents, but to an interrupted convection current of frictional electricity. Since this must flow with moderate velocity, as its inequalities sweep by each little world, the whole spindle of magnetism is not simultaneously affected, but from end to end, in consonance with the motion of the electric cloud, rolls a magnetic billow. This first breaks upon the planet where the sun is seen in the zenith, and sweeps in a widening wave to the planet's rim, vanishing lastly in the centre of the night. If the ethereal billow be of vast proportions, the increased intensity of the whole magnetic field is sustained, with minor fluctuations, until its end sweeps by; whereupon a subsidence of magnetic intensity follows the retreating ethereal wave. If the electric clouds be small and numerous, a number of pulsations occupy at once the magnetic field.

Time observations of the sharper fluctuations, as indicated by needles or helices in opposite hemispheres, supply the means of determining the velocity of the solar atmosphere, and the amount of aberration. This velocity known, the mere timing at a single station of the beginning and ending of the passage of an electric cloud, becomes the measure of its sunward length in miles; its varying breadths can be estimated from the intensity of the magnetic field, and the eccentricity of its position with respect to the globe by the differential indications of antipodal needles.

In the sun's atmosphere must exist depressions below the normal intensity. The effect of these upon the wires and needles is opposite to that of the billows. Their extent and relative position are to be determined in the same way.

From the continuous magnetical observations of even a single station on the earth, when properly interpreted for the hour of the day and the day of the year, can be deduced an accurate record of the variations in intensity of the solar atmosphere,—a record useful in the study of the sun. The law is simple. The passage of a solar wave of intensity higher than the normal, increases, and the passage of a solar depression of intensity lower than the normal, decreases, the average deflection of the needle for that time and place, whether the deflection be eastwardly or westwardly.* For instance, the solar wave increases the eastwardly deflection of the northern night, but also the westwardly deflection of the northern day; and these indications should, therefore, not be separated. At summer solstice, it increases the easterly deflection at both dusk and dawn; but, at the winter solstice, it increases the westerly deflection at these times. The solar depression, at these times and places, reduces the deflections. When the irregular variations are separated into those that increase the average deflection, whether it be eastwardly or westwardly, and those that decrease the average deflection, whether it be eastwardly or westwardly, we have a continuous record showing with great precision the positions and amplitudes of the waves and depressions of the solar atmosphere.

The varying intensity of the solar stream is to be determined by reducing the deflection of the needle to a standard magnetic moment. With a constant solar intensity of any value, the magnetic moment is a function of the needle's distance from the axis of the spindle, and of its direction relatively to the solar rays. This function can be deduced directly from the laws of magnetism. For any station it is easy to derive expressions for the needle's distance and direction, each independently, in terms of the time of day. Thence, by elimination, the variation of the magnetic moment can be expressed in terms of time. The deflection of

* This law is true, whatever the declination of the magnetic meridian from the geographical meridian may be. In most of the illustrations and discussions that precede and follow, it is, for convenience of description, assumed that the magnetic meridians are coincident with the geographical. The true account of the succession of phenomena at any station is easily deduced from its latitude, longitude and magnetic declination, as before explained, or can be constructed from observation. Whatever this may be, the above law holds true.

the needle should be multiplied by the reciprocal of the magnetic moment for that time. A similar reduction must be made for the position of the earth in its orbit. The result shows the variation of the solar intensity, but not its absolute amount. The scale of measurement can be established by a single determination of the quantitative relation between the deflection of a certain needle at any distance from the axis of the spindle and lying in any direction relatively to the solar rays, and the corresponding quantity of electricity that must flow by the earth per second through each square meter of an unlimited cross-section. Dividing this by the velocity of the solar stream, we may ascertain the quantity of electricity contained in each cubic meter at the earth's orbit, and thence the total amount discharged per second by the sun.

These determinations from the data collected at a single station are liable to the following principal errors, so far as they relate to solar intensity; that error arising from the unknown difference in intensity upon the daylight and night-time hemispheres ; that arising from the unknown difference in intensity upon the hemispheres of dawn and dusk ; that arising from the unknown proportions of the magnetic spindle ; that arising from the unknown thickness of the terrestrial atmosphere. The simultaneous records of separated stations afford the corrections, and the means of determining the unknown values. But, with the velocity of the celestial stream known, and that of the earth's rotation, the relative intensities of magnetic influences at daybreak and nightfall upon the needles, wires, and the earth itself, can independently be deduced directly from the laws of magnetism. The effect of declination upon the magnetic moment, and the effect of aberration, are always to be considered.

Obviously, the irregular variations of magnetic intensity, being due to changes in the solar matter adjacent to the earth, spring from a single point on the sun's surface. To find this point the following plan may serve. Assume a value for the time required for the matter to flow from sun to earth,—a week according to the estimates already made. Determine the angular distance of the earth's position a week hence from the sun's equatorial plane. Describe upon the sun a circle of latitude at the

same angular distance from the equator. From this circle issues the matter that will encounter the earth a week hence. The point on the circle is found approximately thus: From the distance that the earth will travel in the ensuing week, as projected upon the sun's equatorial plane, and measured normally to the line joining at present the earth and sun, subtract the distance that a point upon the photosphere in the latitude determined will travel in a week. Extract the angle whose sine or tangent is this difference divided by the earth's distance from the sun, and lay off this angular distance upon the circle of latitude eastwardly from the plane through the sun's poles and the earth's centre. Through the point thus reached sweep by, borne by the sun's rotation, the inequalities of the photospheric surface,—the pores and faculæ and occasional spots,—that send their ever-varying electrical impulses to be intercepted a week later by the earth's observatories. The beginning and the ending of the transit of each distinguished inequality should be recorded in time, and, then, the subsequently produced records of magnetic disturbances should be searched for a succession of inequalities of the same durations, and separated by the same intervals.

The indications of a single inequality will appear less definite at the earth than at the sun, on account of the continual diffusion of impulses. This diffusion will augment the duration of the magnetic transit in comparison with that of the corresponding photospheric transit, if the intensity of the impulse be great; and will diminish the duration, if the intensity be small. Hence, the intervals between inequalities must chiefly be regarded. When such coincidence is discovered between the two records, the time interval between them is the time required for the sun's material emanations to make their journey to the earth. With this true time and a formula of more refinement than that used, the exact point can for any instant be fixed upon the sun's sphere.

The point of emanation is not stationary. It is always a little eastward of the plane through the earth's centre and sun's poles, but moves north and south between the sun's tropics in a line not coincident with a meridian, but depending upon the elements of the earth's orbit, the inclination of the sun's axis thereto, and the rates of rotation of the photo-

spheric zones, and upon the secular variations by which these values are affected. The apparent position at any terrestrial station also varies with the diurnal and annual variations of parallax. The complete oscillation is performed in a year. As the surface of the photosphere sweeps by, upon it is traced a determinable sinuous line, lacing the sun's waist.

Continuous observation of this line as it develops, in connection with a study of the parallel indications of magnetic needles and wire currents, may lead to the following results:

If, in general, the passage of a great sun spot increases magnetic intensity, it is to be inferred that the positive electric charge emanates from the vaporization at the sun's nucleus, and is reduced by the recombinations in the photosphere.

Since the same difference must exist between the dark pores and bright specks of which the photosphere is constituted, the subsequent blending of their products accounts for the zodiacal light. The intensity of the electric discharge in the solar atmosphere exterior to the photosphere, varies inversely as the difference in material quantity of the products positively charged and neutrally charged. If the photosphere were an unbroken region of recombination, the exterior atmosphere would be neutral; no discharge would take place, and no magnetic manifestations in planets. If the photosphere did not exist, the solar atmosphere would be more powerfully charged; the magnetic manifestations in the planets increased; but still there would be no discharge. The maximum discharge occurs when the quantity of matter emanating from the pores and spots is equal to that which flows from the specks of light. This equality seems to be more nearly approached in the equatorial belt than toward the poles, which accounts for the lenticular shape of the zodiacal light, and its extension in the equatorial plane, without requiring a consideration of variation in material density.

Since the intensity of magnetic effects depend upon the excess of free positive electricity over free negative, the discharges that take place between these do not change the resultant magnetic intensity. This intensity simply increases with the increase of area occupied by dark spots, which is in

agreement with well ascertained facts. We may thus find to be true what is very likely, that the solar atmosphere possesses inequalities in electrical intensity,—true electric clouds,—which affect the needles and the currents in the manner heretofore described. In the development of the theory we have hitherto confined ourselves to the equally probable and efficient hypothesis, that the solar atmosphere varies in material density and speed.

It is not to be suspected that the passage of a sun spot by the point of emanation reduces the magnetic intensity,—although this accounts as well for the zodiacal light in all its particulars,—because it is contrary to the often observed fact that increase in the number of sun spots is accompanied by an increase in the diurnal range of the needle's variation in declination, and because it seems less likely that the photosphere should be a separator of electricities than a combiner.

The correspondence between the indications of the magnetic needle and the happenings at the point of emanation being noted, it may be possible from the continuous record of the one to interpolate the interrupted observation of the other, as the sun is obscured by clouds and night. On the other hand, by interpreting the phenomena of the solar point, we may be enabled to predict magnetic weather several days in advance.

Incurving toward the equator of the solar streams in the nether atmosphere has been suspected. If this continue through the outer space, the most delicate observations upon the point of emanation and its immediate vicinity. will be required to make it known.

Thus all the irregular fluctuations in the magnetic fields surrounding the earth, both the primary and the induced, depend solely upon the changes that occur in the point of emanation. Therefore, the record of irregular variations in needles and wires, and in the mean daily intensity of the planet's permanent magnetism, should sometimes show a repetition of sequences, each equal in length to the rotation period of that latitude of the photosphere occupied by the point of emanation, due to the sweeping by in succession of the same irregularities through more than one rotation, when those irregularities are maintained for so long a time.

It is also likely that such repetitions should occur most frequently when the point of emanation is near the sun's tropics, where its motion in latitude is slow, and should occur least frequently when the point is near the equator, where its motion in latitude is rapid, and likely to carry it, in the time of the sun's rotation, beyond the influence of the solar irregularities of the previous period.*

The permanent magnetism of the earth is derived from the solar stream that issues from the point of emanation in the long course of time. Since this point, in the course of time, traverses every part of the sun's equatorial belt, and no other part of the solar surface, the earth's permanent magnetism is derived entirely from the sun's tropical belt.

With the velocity of the solar atmosphere at the earth's orbit ascertained, and the time required for the passage of its particles from the sun, we can approximate closely its velocity as it emerges from the photosphere, for the same reason that, when the initial and final velocities of a body are known, and the distance traversed, the time of passage can be very nearly determined, although the mode of variation of velocity is imperfectly known. The expression (50) may be re-written thus :

$$v^2 = v_h^2 + \frac{2\varkappa}{\varkappa - 1} \cdot \frac{p_h}{D_h} \left\{ 1 - \left(\frac{v_h r_h^2}{v r^2} \right)^{\varkappa - 1} \right\} - 2 g_h r_h \left(1 - \frac{r_h}{r} \right), \qquad (102)$$

where the symbols distinguished by the subscript, h, denote the values at the earth's orbit. This formula is exact for a non-cendensible gas, but only roughly approximate for the sun's atmosphere. Nevertheless, it is entirely sufficient to obtain the velocity at the photosphere, when the time of passage is known, as was just explained. This velocity could immediately be extracted, if the co-efficient

$$\frac{2\varkappa}{\varkappa - 1} \cdot \frac{p_h}{D_h}, \qquad (103)$$

were known. It is the knowledge of the time that determines this co-efficient for the purpose of the problem. If the gas were non-

* Such repetitions, of about 26 days' period, have been noticed by Broun and by Hornstein. Broun's tabular statement for the years 1844-1845 is quoted in *Encyclopædia Britannica*, Article, *Meteorology*, p. 177, wherein it appears that the repetitions in every case but one occur near the times of the solar tropics.

condensible, the velocity could thus be obtained exactly; as it is, the velocity can be found with close approximation.

Assume first that the velocity varies as the distance. Then

$$\frac{v_b + v_h}{2} = \frac{\text{Distance}}{\text{Time}}. \tag{104}$$

Here the only unknown quantity is v_b, the velocity at the photosphere's outer surface. Find its value and substitute in (102). So determine approximately (103). Substitute this value in (102), and find v at intervals of one million miles from the photosphere outward to a distance of five million miles; and, thereafter, at intervals of five million miles to a distance of thirty million miles; and, thereafter, at intervals of ten million miles to the earth's position. From these values of v, each assumed to be constant for half the interval on each side, compute the time of passage; compare with the true time; correct the co-efficient (103), and proceed again. So continue until a value of (103) is found that will agree with the true time. When this is found and placed in equation (102), the resulting value of v_b is very nearly the velocity of the solar atmosphere at the outer surface of the photosphere.

The ascertainment of the velocities of the solar atmosphere at the photosphere and at the earth's orbit, simplifies the problem of the sun's temperature, leaving it indeterminate only as it depends upon the relative density of the atmosphere as compared with hydrogen. Equation (97) may be written

$$\frac{\tau_b - \tau_h}{\delta} = \frac{1}{(.105)^2} \left\{ v_h^2 - v_b^2 + 2g_b r_b \left(1 - \frac{r_b}{r_h}\right) \right\}, \tag{105}$$

and the true value of the ratio nearly approximated. Further than this the processes of these pages do not lead.

Somewhat of the laws of the variation of density and velocity in the solar atmosphere, in terms of the distance from the sun, as they differ more or less from the laws for a non-condensible gas, exhibited in expres-

sion (49), can be learned by a comparison of observations made at divers points in the earth's elliptic orbit; for the natural density varies as the electric density, and the latter can be found as explained. The mean of many years' observations should be used at each point, in order to eliminate the irregular variations. This problem involves the simultaneous discussion of the variation in electric intensity of the solar latitudes. The combined effects of the two causes upon terrestrial magnetism can be separated by analysis.

The inequalities in the solar atmosphere, which become smoothed and blended as they flow, must be tremendously steep and rugged near the sun. Very great must be the irregular vibrations of the needle in the planet Mercury, much less in Venus, diminishing from the innermost planet to the outermost.

BETWEEN the ever renewed positive electricity of the celestial regions, from the surface of the magnetic spindle outward, and the ever present negative electricity in the planet's crust, thither drawn from the centre by electrical attraction, lies the planetary atmosphere, touching the negative surface at all points, and the positive chiefly in the zone of tangency. The eddies in the solar stream that occupy the ends of the magnetic spindle, are not potent factors, because their material is but slowly changed. So the region of maximum electrical intensity in the upper or positive surface, is a zone passing through the poles, and extending above the meridians of dawn and dusk ; and the region of maximum intensity in the negative, or lower, surface, passes likewise, through the poles, and extends along a meridian of the forenoon and a meridian of the early night, removed eastward from the dawn and dusk meridians by the whirling of the sphere. What happens in the planetary atmosphere, as these opposite electricities transpire, is easily deduced.

If the atmosphere be a non-conducting, permanent gas, the interchange of electricities is exceedingly slow, being effected merely by the transference of particles in contact with one surface to the other by the action of air currents in the long course of time, aided by the attraction of each surface for particles oppositely charged. The electric potential of such an atmosphere increases regularly from the negative to the positive surface.

If the atmosphere be partially composed of vapors that rise, condense and fall, the interchange of electricities is much more rapid. First consider the case where evaporation is so moderate that the aerial envelope does not thereby become a conductor. The vapor particles, as

at different altitudes, is manifest in water-falls, which, bearing with them the denser negative charge of the upper ledge, render the air through which their spray is strewn, negative with respect to the basins where they plunge.

Next consider what happens when, at any part of the planet, evaporation is so vigorous that the overlying atmosphere becomes a conductor of electricity. The column of vapor is then virtually a portion of the planet's crust and acts like a solid projection. Negative electricity rushes up the column until conductivity ceases where the main portion of vapor condenses into cloud. The negative potential at this summit becomes very great in comparison with that of the ground. Thus a wide region under the sun's hot rays may have its negative charge lifted a mile into air, but the highest potential, and the intensest effects, are present in the narrowest column that can rise.

Above, the uncondensed remainder of the vapor still ascends as an imperfect conductor, and rapidly becomes positive, as in the case of slow evaporation from the ground. In that direction the discharge takes place. Bolt after bolt darts upward from each column's top, while neither rain falls nor thunder is heard. Far off toward the horizon, the sparks are indistinguishably blended into momentary flashes that seem to be beyond the clouds, and illuminate their ragged borders.* The action abates when the column that connects the ground and cloud is broken by decline in the vigor of evaporation, and ceases when the potential of the then insulated charge is sufficiently reduced.

* The writer witnessed such a display, between eight and nine o'clock, P.M., July 14th, 1891, at City Island, New York, in a great cluster of clouds reaching from the horizon to an elevation of twenty degrees. That the phenomenon was not due to reflection of more distant storms, was rendered certain by the fact that the flashes in the nearer and farther clouds were not simultaneous, and that the nearer were much brighter than the farther. It was, indeed, evident, in case of the nearer flashes, from every feature, that they originated in the clouds' substance where they were seen. The same clouds, apparently, had delivered thunder showers and bolts to the earth in the afternoon.

Sometimes, at nearer view, the fiery darts themselves are seen, as thus described on page 198 of Vol. 1, *American Meteorological Journal:*

"A large cloud had amassed beyond the Susquehanna, and seemed to stand like a great mountain peak on the summit of Peter's mountain, surrounded by a clear atmosphere. For more than an hour it was in a constant blaze from the streams of electricity that darted momentarily, like fiery serpents, in every direction through it. Often they would dart into the clear atmosphere and branch out like leafless trees, and often dart directly upward from the top of the cloud."

Although the natural tendency of the negative electricity induced in the top of the vapor column, is to discharge itself into upper space, and although there is no tendency whatever to discharge to the ground, while the conditions under which that electricity was collected are maintained, yet a lowering of the negative potential in the planet's crust, caused by the passing away of the negative crest of the electric tide, and the approach of the negative hollow, or by a lessening of the distance between cloud and ground, as the former sinks, or is carried by upper currents toward highlands and mountains, originates a tendency in the electric charge to return to the planet's crust. If the column remain unbroken, the descent is as quiet as the rising; but, if the charge be insulated by the decline of evaporation, or the sweeping away of the cloud, the excess of negative potential in the cloud over that due to its altitude and the state of the planet's crust beneath, can only pass downward by disruptive discharge. The difference of potential between the negatively charged cloud and the ground, is generally less than between the cloud and a stratum above as far distant; but the resistance downward is also generally less. What remains of the cloud after discharges by rain and flashes, ultimately becomes positively charged by contact with the atmosphere.

So the normal electrical condition of the planetary atmosphere is positive with respect to the surface of the globe.* Vapor that has been generated slowly, or that is widely diffused, or that has been in the atmosphere a long while, is positive. Vapor that issues in thick volumes is for a time negative. The curl-clouds and the stratus are repositories of positive electricity; the cumulus are powerful reservoirs of negative electricity.

How electricity becomes condensed in portions of the atmosphere is

* "The presence of electricity in the upper regions of the air is not confined to thunder-clouds, but can be detected at all times. In fine weather this electricity is almost invariably positive, but in showery or stormy weather negative electricity is as frequently met with as positive; and it is in such weather that the indications of electricity, whether positive or negative, are usually the strongest."

"As we proceed further from the earth's surface, whether upwards from a level part of it, or horizontally from a vertical part of it, such as an outer wall of a house, the potential of points in the air becomes more and more different from that of the earth."

"We obtain stronger indications on hills than in valleys."

Deschanel's *Natural Philosophy*, Translation by Professor Everett, 1881, pp. 644, 647, 648.

easily explained. As the thin mist, visible or invisible, of the upper regions falls, bringing down in its particles a high positive potential, it eventually, in the average state of the atmosphere, encounters an unsaturated stratum. Here its downward journey is arrested ; for, the mist is redissolved and floats, or slowly reascends to be reliquified. Meanwhile the mist from far above continues to descend and gather at the boundary of the unsaturated stratum. As the bank of vapors hourly, or daily, grows thicker and denser, it also works its way slowly downward, by saturating the upper portions of the lower stratum. Thus the potential of the region of the forming cloud is powerfully raised, both by the descent, and the condensation, of vapor. When, in this kneading process of floating or rising vapor and falling mist, the particles have become large enough, rain falls; and lightning darts to the ground or lower air as soon as the resistance is sufficiently reduced. Such lightning is positive and always strikes downward. If the lower stratum of the atmosphere be saturated, such action does not take place, but the falling mist of the upper region continues to fall to the ground merely as mist.

The reverse process of a slowly rising vapor from the ground condensing in the upper regions, produces only a small positive charge, because the potential of the rising electricity is very low. Positive thunder storms can only be generated by the fall of mist from higher regions of the atmosphere.

Negative electricity is condensed with the condensation of the vapor that rises from the ground, when the process is not too slow. If evaporation is vigorous, little of the negative charge is lost in the swiftly rising column. The intensity of the charge is greatly increased when the column itself becomes a conductor, as before explained.

The negative thunder-cloud is necessarily quickly generated and short-lived. The positive thunder-cloud is necessarily the product of a slow process, and is subject to many vicissitudes. Hence negative thunder storms are more frequent than positive Their intensity is apt to be greater, too; for, their charge comes to them by conduction and convection both, and not by convection only.

As these opposing forces range their armies in the aerial fields, the

difference in the afternoon and before dawn, at the time of the passing of the negative hollows.* The diurnal variation is greatest at the equator, and diminishes to zero at the poles.

The same variation of potential exists in all projections, its range increasing with the height and sharpness. Hence the phenomenon of St. Elmo's fire should occur oftenest at the passing of the negative crests, that is, in the forenoon, if then it could be seen, and in the early night. So, too, the electric displays accompanying volcanic eruptions and the whirling vortices at sea. For the same reason, the discharges from vapor columns to the space above, commonly called *heat lightning*, is a phenomenon that belongs to the early day and early night, except that the columns are not likely to exist near morn.

Disruptive discharges in the lower atmosphere, which constitute thunder-storms, are, as has been shown, chiefly the return of negative electricity from insulated clouds previously charged by induction through conductive vapor columns. Hence thunder-storms, so far as the electric tides affect them, should occur most frequently at the passing of the negative hollows, that is in the afternoon and before the dawn of day. But, as in the case of heat lightning, since the night is unfavorable to the formation of dense columns of vapor, the maximum of the hemisphere of dawn cannot in general exist.†

* The times of the maxima are, at Kew Observatory, nine A. M. and nine P. M., near the equinoxes. Deschanel's *Natural Philosophy*, Translation by Prof. Everett, 1881, p. 650.

The theory of this paper indicates that the night maximum is nearer to dusk than the day maximum is to dawn, on account of the greater intensity of the zone of tangency on the daylight side than on the dark.

† Over Mauritius in the Indian Ocean sweeps steadily the moist monsoon from the end of October to the middle of May, flowing southwestwardly from India. This stream of dense, warm vapors overcomes the local variations of diurnal time. Here we find the daily curve of frequency of thunder-storms exhibits two maxima, the greater from noon to four P. M., the lesser from three to six A. M., and two minima, from nine P. M. to one A. M., and from eight to ten A. M. See *Encyclopædia Britannica;* Art., *Meteorology*, p. 128.

At the head of the Adriatic the greater maximum is from eleven A. M. to four P. M., the lesser from two A. M. to four A. M.; the minima occur between ten P. M. and one A. M., and between five A. M. and nine A. M. *Encyc. Brit.*, p. 129.

But the general conclusion, from a wider survey of the phenomenon, is that the maximum occurs, in the hottest months, between three P. M. and four P. M., and the minimum from four A. M. to five A. M. *Encyc. Brit.*, p. 128.

The variations due to latitude are these;

The zone of tangency induces upon the planet's surface a band of negative electricity of uniform width and potential.* The surface potential diminishes from every part of this band to the centres of the circular spaces it separates. If, now, the surface be divided into belts bounded by circles of latitude, it is evident that the mean negative potential of the planet's surface increases rapidly from the equator to the poles.

Conceive concentric spherical surfaces to be described within the globe at small intervals from crust to centre. The mean negative potential on each of these spheres increases from equator to poles; and the mean difference of potential between any two spheres increases from the equator to the poles. The negative potential increases from centre to the crust.†

Conceive concentric spheres to be described without the globe at small intervals from its crust to the upper limit of the atmosphere. The mean negative potential on each of these spheres increases from the equator to the poles, and the mean difference of potential between any two spheres increases from the equator to the poles. The negative potential decreases from the ground to the celestial stream.

In other words, the mean difference of potential between ground and air increases with the latitude, and the absolute negative potential of any layer of air increases from equator to poles, although this layer becomes more positive relatively to the underlying crust as the distance from the equator is more.

The capacity of the atmosphere for holding moisture, and, therefore, electricity, increases with the temperature. So great is the variation of capacity due to latitude that, notwithstanding the opposite variation of negative potential, the quantity of negative electricity contained in the lower atmosphere is vast at the equator, and diminishes rapidly to the poles.

* The rotation increases the width and reduces the potential toward the equator in a way that does not affect the results mentioned in this paragraph.

† If metallic rods be set vertically in the ground, each terminating aloft in a ball, and insulated from the air, the mean difference of potential between the top and foot of the rod will be found to increase with the latitude of its position. In the rod on the equator the difference of potential will be greatest at the passing of the negative tides.

Lightning is caused by great local differences of potential between portions of the air, or between the air and ground. The generation of these great local differences of potential increases with the mean difference of potential between layers of the air, and between ground and air; with the quantity of vapor and electricity; with the difference in temperature between atmospheric strata; and with the variation of the electric tides. The first of these conspiring causes increases slowly with latitude; each of the other three decreases rapidly with latitude. Hence electrical displays in the lower atmosphere diminish in frequency and intensity from the equator to the poles.

Thus, dense vapor columns, the producers of negative thunder storms and of heat lightning, become less frequent as the latitude is greater. Although the proportion of positive storms to negative naturally increases with latitude, even the positive storms decrease in frequency; because the rarer vapors of the colder climes, requiring a longer time to settle and collect their forces, are subjected to more vicissitudes, so that seldom can they reach the potential necessary for disruptive discharge. The regularity of the variation from equator to poles is much disturbed by winds and many well-known causes affecting the quantities of moisture in the air.

Consider, next, the upper atmosphere. The temperature of each spherical layer is nearly uniform about the planet, and remains nearly uniform in the course of time. The rate of diffusion of vapor is rapid on account of the thinness of the permanent gasses. The space is always saturated with vapors on account of the copious supply in the lower atmosphere, and the uniformity of temperature. Hence, the density and quantity of vapor are nearly uniform about the planet. Consequently, the electric capacity of each layer of the upper atmosphere is nearly uniform through space and time. The electric potential of the upper vapors is derived from that of the denser lower atmosphere immediately beneath, and is not affected by the quantity of vapor and electricity in that lower region. Hence the potential and, consequently, the quantity, of negative electricity increases rapidly from equator to poles. The highest regions are conductors of electricity on account of the extreme rarity of the permanent gases.

Since the capacity and resistance of the upper atmosphere are nearly uniform about the planet, the rate of transpiration of electricity increases with the difference of potential between the celestial stream and any concentric spherical stratum of the upper atmosphere, and hence increases rapidly from the equator toward the poles.

This modification must be noted. The interchange of electricities tends to reduce the negative potential of the upper atmosphere, and this potential is maintained by supply from the lower atmosphere. Since the capacity of the upper strata for vapor and electricity is limited, it matters not, in the maintenance of potential, how superabundant the quantity of electricity in the lower atmosphere may be; but the potential of the upper strata falls if the quantity in the lower strata is insufficient to maintain it. Accordingly, in a cool planet, which suffers slight evaporation at the poles, the maintained negative potential of the upper strata, and the transpiration of electricity, increase rapidly from the equator to the latitude where the quantity in the lower atmosphere is just sufficient to maintain the potential in the upper, and thence decline to the poles. If, as in the case of the earth, the difference in the rate of evaporation is sharply defined by the existence of ice-caps at the poles, the maintained difference of potential, and the transpiration of electricity in the upper atmosphere, abruptly decline from the latitude of the maximum to the poles.

The interchange of electricities takes place between the zone of tangency of the solar stream, which stretches widely into the hemispheres of day and night, and the underlying strata of the atmosphere. Hence the maximum discharge should be at the four intersections of this zone with the latitudes of maximum, which are irregular lines governed by the topography of the planet. But, in the lower atmosphere, the vapors rise by day, bearing up negative electricity, and fall at night, carrying down positive, so rendering the potential of the upper strata higher at nightfall than at dawn; so that, finally, the places of maximum discharge of electricities between the solar atmosphere and the planet's, are at the intersections of the north and the south irregular latitudes of maximum with the meridian of dusk, reaching somewhat into day and into night.

The discharge of the electricity through the rarefied air of the upper

atmosphere is accompanied by a glowing such as is seen in Geissler's tubes. It is visible or invisible as the strength of the current is greater or less. It is most often to be seen in the regions of maximum discharge.* The appearance of its under surface from every point of view is that of an arch parallel to the underlying portion of the planet's crust. The upper part fades away toward the solar stream. Its altitude varies at different times, as the equipotential surfaces of the atmosphere shift their positions, and according to the prevailing intensity of the solar stream.

Such is the electrical condition of the planet's atmosphere at the equinoxes. The annual variations are these:

As the planet moves from vernal equinox to summer solstice, at any place in the northern hemisphere the two diurnal times of maximum ground potential, or of maximum difference of potential between ground and air, depart from noon and approach the midnight. This recedence from noon is more rapid as the latitude increases: on the equator it is nothing; on the polar circle the two maxima reach coincidence at the solstice; nearer to the pole, the coalescence is sooner reached. In the southern hemisphere the times of maximum ground potential similarly approach the noon.

The effects upon the semi-diurnal ranges of variation in ground potential, and upon the mean semi-diurnal ground potential, in the several latitudes, are apparent.

Whereas at the equinox the maximum range of ground potential is at the equator, and the minimum at the poles, now, while the planet recedes from the equinoctial point, the range at the equator continually diminishes until the solstice is reached. In any north latitude between the

* Auroras occur more frequently before midnight than after. *Encyc. Brit.*, Art., ***Aurora***, p. 98.

"The zone on the earth's northern hemisphere where auroras occur most commonly and attain their greatest splendor, may be represented by constructing a ring of card or paper, of such dimensions as to agree with the 60th parallel of north latitude, and then pushing the ring southward on the side of America and northward on the side of Asia, until it passes through the most southerly part of Hudson Bay, and the most northerly part of Siberia." *Amer. Cyc.*, Art., *Aurora Borealis*, p. 121.

"Capt. McClintock observed in the Arctic regions that the Aurora was never visible above ice fields, but that whenever an aurora was in progress the light appeared always to be gathered over the surface of the open water." Ibid., p. 123.

equator and the tropic, the daylight range increases until the sun has climbed to that latitude, and thereafter decreases. In any latitude between the tropic and the polar circle the daylight range continually increases. In any latitude nearer to the pole the daylight range increases until the entire circle of latitude is lighted by the sun. Thereafter the variation is ambiguous,—without closer analysis. Between the equator and the south polar circle, the range continually decreases. Between the polar circle and the pole, the daylight range of any latitude decreases until the entire circle of latitude is in the dark. Thereafter its variation belongs to the night. The night-time variations of the southern hemisphere are exactly like those of the northern day; and the variations of the northern night like those of the southern day.

The variation due to latitude in the diurnal range of ground potential diminishes continually. In the case of a planet whose rotation axis lies in the orbital plane, the variation due to latitude, together with the diurnal range itself, vanishes at solstice.

Whereas at the equinox the minimum mean diurnal ground potential is at the equator, and the maximum is at the poles, now, in the planet's passage from the equinoctial point, the mean potential at the equator increases to the solstice. The mean ground potential of the northern day diminishes at every point between the pole and a circle of latitude nearer to the equator than the northern tropic, the minimum being reached at the solstice. Between this latitude and the equator the mean ground potential first decreases and then increases. Southward of the equator, the mean potential increases at every point to the polar circle. Nearer to the pole the mean potential first increases and then decreases. The changes in the northern night are like those of the southern day, and the changes of the southern night like those of the northern day.

When the divergence of the equatorial plane from the orbital plane is small, the variation due to latitude in the mean diurnal ground potential continually diminishes until the solsticial point is reached. But when this divergence is great, the variation diminishes until it vanishes, that is, until the mean diurnal potential at the poles and at the equator is the same. Thereafter the variation is reversed, the mean potential at the

equator becoming greater than at the poles, and this difference increases to a maximum at the solstice.

From summer solstice to autumnal equinox these variations are reversed. Thence on through winter to the vernal equinox, the southern night and northern day are affected as the other quarters were in summer time; and the northern night and southern day have likewise exchanged their variations with the other quarters of the sphere. But the variations due to latitude in the diurnal range of ground potential and in the mean diurnal ground potential, are the same from vernal equinox through summer to the autumnal, as from autumnal to the vernal.

Thus, in general, the approach of its own summer to any latitude causes the times of maximum negative ground potential, or of maximum difference of potential between ground and air, to depart from noon and approach the midnight; and the approach of its own winter causes the times of maximum to approach noon and depart from midnight.*

The approach of its own summer to any latitude causes the daylight range of variation in ground potential to increase, and the night-time range to diminish; and the approach of its own winter causes the daylight range to diminish, and the night-time range to increase.†

The approach of its own summer to any latitude decreases the mean diurnal negative ground potential by day, and increases it by night; and the approach of its own winter increases the mean ground potential by day, and diminishes it by night.‡

* Observations in the earth's northern hemisphere agree with the theory. The author has seen no record of observations made at southern stations. Thus, Deschanel on page 650 of *Natural Philosophy* says:

"The Kew observations, being continuous, are specially adapted to throw light on the subject of diurnal variation. They distinctly indicate for each month two maxima, which in July occur at about eight A. M. and ten P. M., in January about ten A. M. and seven P. M., and in spring and autumn about nine and nine. The result of the Brussels observations is about the same."

In R. H. Scott's *Elementary Meteorology* it is stated that the maxima occur in summer at about eight A. M. and nine P. M.; at ten A. M. and six P. M. in winter. The daylight minimum occurs about three P. M. in summer and one P. M. in winter, the night-time minimum not being satisfactorily determined.

See also *American Meteorological Journal*, Vol. 3, p. 523 *et seq.*

† The writer has seen no record of observations of this kind.

‡ The writer has seen no record of observations of this kind taken at night or in the southern hemisphere. Deschanel says on p. 649 of his *Natural Philosophy*:

"Observations everywhere [the remarks in this section express the results of observation at places all of

The approach of the planet to either solstice causes the variations due to latitude, in the diurnal range of ground potential, and in the mean diurnal ground potential, to diminish.*

These generalizations, useful in the deduction of the annual variations of thunder-storms and polar auroras, apply to a planet whose orbital and rotation planes diverge not greatly; they are true of the temperate zones, and nearly so for a wide reach beyond, but are not applicable, as the more precise preceding statement shows, to polar caps and tropic belt. To a planet whose seasons are like those of Uranus, these generalizations do not apply

The frequency of negative thunder-storms varies with the variations of the following conditions necessary to the existence of negative thunder-storms.

(1) The frequency increases with increase of evaporation.

(2) The frequency increases with increase in the diurnal range of the variation of ground potential.

(3) The frequency increases as the maximum negative ground potential approaches that part of day when the most copious evaporation takes place.

So far as the first and second conditions are concerned, thunder-storms should occur more frequently in summer than in winter throughout the temperate zones, and even to the poles. So far as the third condition is concerned, thunder-storms should occur more frequently in winter than in summer. The potency of the third condition increases rapidly with latitude. Hence the conclusion is this:

Thunder-storms occur more frequently in summer than in winter in

which are in the north temperate zone], concur in showing that the average strength of potential is greater in winter than in summer; but the months of maxima and minima appear to differ considerably at different places. The chief maximum occurs in one of the winter months, varying at different places from the beginning to the end of winter; and the chief minimum occurs everywhere in May or June. Both Kew and Windsor show distinctly two maxima in the year, but Brussels, and apparently Kreuznach, show only one. The ratio of the highest monthly average to the lowest is at Kew about 2.5, at Windsor 1.9, and at Kreuznach 2.0."

See, also, tabular and other statements in the *American Meteorological Journal*, Vol. 3, pp. 523–528.

* The writer has seen no record of observations of this kind.

the portions of the temperate zones nearer to the equator. The annual variation decreases with latitude and is reversed in the portions of the temperate zones nearer to the poles, where thunder-storms occur more frequently in winter than in summer.

Consider, as an example, the case of Iceland, verging upon the Arctic circle. At mid-day at summer solstice as seen from the sun, this island is as far removed from the planet's northern rim as is Philadelphia or Madrid at the equinoxes, or as Central America and the southern part of the Desert of Sahara at the winter solstice. The evaporation is far more copious than in winter, but the vapor rises when the negative ground potential is very small. The difference of potential between the top and base of the column is also comparatively small, because the inducing solar stream is thousands of miles away. As rotation proceeds the tendency of the column's top to discharge downward is rapidly diminished, because the approaching solar stream holds the charge aloft, and the growing potential of the ground attracts it less. The possibility of a storm in summer here is small.

In winter at mid-day Iceland is directly under the most potent portion of the solar stream, and only separated from it by the depth of the earth's atmosphere. The ground potential is now at its maximum. The gradient between the positive solar stream and the negative crust is the steepest possible. The inducing power of the solar stream renders the difference of potential between the top and base of any column that may rise, exceedingly great. There is, of course, no tendency to produce a thunder-storm while this induction takes place ; but, as the island sweeps into the night, its ground potential rapidly diminishes, and the solar stream passes thousands of miles away. The tremendous negative charge in the column's top is no longer held there by induction, while the decreasing potential of the ground invites it thither. At midnight the difference of potential is a maximum, and in the night-time the thunder-storms occur. Because strong evaporation is not likely to take place in winter, these thunder-storms are very rare ; but the theory indicates that, whereas it is almost impossible for such storms to occur in summer, in spite of the more copious evaporation, it is, on the other hand, almost impossible that

until it is sufficiently so to allow the vapor to become negatively charged by induction. Then thunder-storms ensue.

It has been shown that the mean diurnal negative ground potential increases from the equator to the poles by less at the solstices than at the equinoxes. Hence the negative potential of the vapors that rise to the upper atmosphere, likewise, increases from equator to poles by less at solstice than at equinox. It follows that at either solstice the transpiration of electricities between the solar stream and the planet's vapors, is greater at the equator and less at the poles than when the planet is near the equinoctial point. Consequently the glow that sometimes accompanies the transpiration is weaker and more distributed at solstice, and stronger and more concentrated at the time of equinox. That is, the polar lights attain to their maxima at the equinoctial points, and reach their minima at the solsticial. Aberration throws the epochs of maxima and minima a little later in yearly time.* In the case of a planet inclined like Uranus, the transpiration at solstice takes place only about the equator, and the aurora, if not too faint to be seen, is a continuous ring encircling the globe.

On account of the eccentricity of the orbit, there is also one annual maximum at perihelion, and one minimum at aphelion, which superimposed upon the former, causes, in case of the earth, the June minimum to be absolutely smaller than that of January.

The theory indicates that polar auroras are essentially independent of planetary magnetism, and would occur in a rotating planet devoid of magnetic material. It is true, however, that the magnetism of a planet re-acts upon the solar stream, and may thus alter somewhat the phenomenon.† The position of the zone of maximum frequency of auroras

* There are two well-marked annual maxima in March and October, of which the latter is the greater, and two minima, the greater in June and the less in January, *Encyc. Brit.*, Art., *Aurora*, p. 98.

† "It has been shown by Prof. Plücker that when an electric discharge takes place through rarefied gas in the field of a magnet, it is concentrated in the magnetic curves."

"Varley shows that when a glow discharge in a vacuum tube is brought within the field of a powerful magnet, the magnetic curves are illuminated." *Encyc. Brit.*, Art., *Aurora*, pp. 96, 97.

in the earth's northern hemisphere can be accounted for by the circum-polar distribution of open water without having recourse to the present position of the north magnetic pole.

Since the auroras are caused by the interchange of the electricities of the sun's atmosphere and the planet's, their light should present the characteristics of the zodiacal light and the corona.*

In brightness and frequency the auroras increase and diminish in consonance with the intensity of the solar stream. Thus, together with the vibrations of needles and the flow of currents through wires, they mark the grand pulsations of the sun.

According to the theory, the sun is becoming negatively charged, and the planets positively charged, with electricity.

* Angström concluded from spectroscopic observation "that in the Zodiacal Light there was the same material as is found in the aurora and in the solar corona." See p. 56 of this essay.

COMETARY ATMOSPHERES

AS comets, entering the range of human vision, approach their perihelia, they exhibit signs of great and rapidly increasing heat.* So small is their mass† that they are very susceptible to changes in temperature, as is shown in formula (33). The less gravity is, the narrower is the range of variation in temperature necessary to cause a body to pass through the category of conditions, and the more rapidly is the transition effected. At the earth's distance the comet receives in caloric from the sun, per square foot per solar day, 5000 pound-degrees, centigrade, equivalent to 6,950,000 foot-pounds, sufficient to lift a ton two-thirds of a mile.‡ In falling from the orbit of Jupiter to that of the earth, the

* "A comet usually consists of three parts, developed, it may be, somewhat in the following manner: A faintly luminous speck is discovered by the aid of a good telescope; the size increases gradually; and after some little time a nucleus appears—that is, a part which is more condensed in its light than the rest, and is sometimes circular, sometimes oval, and sometimes (but very rarely) presents a radiated appearance. Arago remarked that this nucleus is generally eccentrically placed in the head, lying towards the margin nearest the sun. Eddie noticed that the nucleus of Fabry's comet of 1886 was of a ruddy brown color. Both the size and the brilliancy of the object progressively increase; the *coma*, or cloud like mass around the nucleus, becomes less regular; and a tail begins to form, which becomes fainter as it recedes from the body of the comet. This tail increases in length so as sometimes to spread across a large portion of the heavens; sometimes there are more tails than one, and occasionally the tail is much narrower in some parts than in others. The comet approaches the sun in a curvilinear path, which frequently differs but little from a right line. It generally crosses that part of the heavens in which the sun is situated so near the latter body as to be lost in its rays; but it emerges again on the other side, frequently with increased brilliancy and increased length of tail. The phenomena of disappearance are then not unlike those which marked the original appearance but in the reverse order." Chambers' *Astronomy*, pp. 398, 399.

† "The quantity of matter that enters into the constitution of a comet is exceedingly small. Norton's *Astronomy*, 1845, p. 207.

‡ Deduced from the statement found in works upon physics and astronomy, that the heat received by the earth from the sun in a year would melt a layer of ice one hundred feet thick upon the entire surface of the globe. The same quantity of heat would, therefore, melt a layer four hundred feet thick upon a surface normal to the rays and constantly exposed, at the earth's distance.

amount has increased twenty-seven fold. At the perihelia of the comets of 1680 and 1843, the energy received by the former was about 150 billion foot-pounds per square foot per solar day, and by the latter, 200 billions, approximately. Here on the earth this vast energy causes the winds to blow, the clouds to form, the rains to fall, exhibits itself in the roar of cataracts and in the silent growth of forests, in the vagaries of life, the mysterious workings of mind; there in the comet it is solely employed in vaporizing the core and driving off the vapors into space.

Although the atmosphere of the earth is a mere film, it causes many rays to strike the solid globe that otherwise would pass uninterrupted. It is to be inferred that the atmospheres of comets, whose depths are measured by tens of thousands of miles, refract, however thin they be, to the nucleus several fold the number of rays its surface unaided could intercept. The quantity of this refracted energy also increases toward perihelion as the compassing vapors grow more and more dense.*

In the comet's long journey through aphelion as a virtually isolated body, it has ample time to reach a condition of almost quiescent equilibrium, as described in the first paragraph of page 15. The atmosphere presents the aspect **A**, although there is no general descent of vapors. But as heat is newly added in the descent to perihelion, while the force of gravity is not increased, conditions **D** and **E** are likely to supervene.† The rising vapors about the nucleus become limpid, and only condense when adiabatic expansion makes them cool in upper regions. So a visible spherical segment of condensation forms on that side toward the sun, and rises with the growing heat. This rising of the condensation sphere does

* "There are one or two instances on record, where astronomers have been convinced of a sensible increase of brilliancy when a star has been viewed through the cometic vapor. In addition to a remarkable observation of this kind by Piazzi, at Palermo, during the appearance of the grand comet of 1811, we may mention a more recent one by Professor Reslhuber, of Kremsmünster, in reference to a star seen through the denser part of a comet discovered by Brorsen in March, 1846, and which, under ordinary circumstances, belonged to the eighth class, or was just beyond unassisted vision. When the star was centrally covered by the comet, it became very considerably brighter, and was judged to be equivalent to a star of the sixth magnitude, in which case it would have been distinctly visible without a telescope." Hind's *Comets*, p. 23.

This seems to indicate that the cometic atmosphere acted like a lens.

† In many telescopic comets these conditions never become strong, and the nebula maintains the appearance **A**.

not indicate the velocity of the vapors, but simply the increase of nucleus temperature. Further increase of temperature causes less volatile vapors to ascend and condense in a lower region. Thus in succession are formed concentric surfaces of condensation, all moving outward as described on pages 16, 17.*

While the comet is still far distant from the sun, its vapors are being brushed away by the outsweeping of the solar atmosphere. At first vision, this is imperceptible, on account of the great distance, the comparatively slow motion and small density of the solar stream, and the comparative sparsity of cometic vapors. Nearer the sun, the comet's vapors become more copious, and the solar atmosphere grows denser and

* "When comets are studied with a telescope, it is found that they are subject to extraordinary changes of structure. When one of these objects is first seen, it is generally approaching the sun from the celestial spaces. At this time it is nearly always devoid of a tail, and sometimes of a nucleus, presenting the aspect of a thin patch of cloudy light, which may or may not have a nucleus in its centre. As it approaches the sun, it is generally seen to grow brighter at some one point, and a nucleus gradually forms, being at first so faint that it can scarcely be distinguished from the surrounding nebulosity. The latter is generally more extended in the direction of the sun, thus sometimes giving rise to the erroneous impression of a tail turned towards the sun. Continuing the watch, the true tail, if formed at all, is found to begin very gradually. At first so small and faint, as to be almost invisible, it grows longer and brighter every day, as long as the comet continues to approach the sun.

"If a comet is very small, it may undergo no changes of aspect, except those just described. If it is an unusually bright one, the next object noticed by telescopic examination will be a bow surrounding the nucleus on the side toward the sun. This bow will gradually rise up and spread out on all sides, finally assuming the form of a semi-circle having the nucleus in the centre, or, to speak with more precision, the form of a parabola having the nucleus near its focus. The two ends of this parabola will extend out further and further so as to form a part of the tail, and finally be lost in it. Continuing the watch, other bows will be found to form around the nucleus, all slowly rising from it like clouds of vapor. These distinct vaporous masses are called the *envelopes*: they shade off gradually into the coma so as to be with difficulty distinguished from it, and indeed may be considered a part of it. The inner envelope is sometimes connected with the nucleus by one or more fan-shaped appendages, the centre of the fan being in the nucleus, and the envelope forming its round edge. This appearance is apparently caused by masses of vapor streaming up from that side of the nucleus nearest the sun, and gradually spreading around the comet on each side. The form of a bow is not the real form of the envelopes, but only the apparent one in which we see them projected against the background of the sky. Their true form is similar to that of a paraboloid of revolution, surrounding the nucleus on all sides, except that turned from the sun. Each is, therefore, a surface and not a line. . . . . Two or three vapor surfaces of this kind are sometimes seen around the comet, the outer one enclosing each of the inner ones, but no two touching each other.

"This motion, it will be seen, is not very unlike that of water thrown up from a fountain on the part of the nucleus nearest the sun, and then falling down on all sides. The point in which the motion of the cometic matter differs from that of the fountain is that, instead of being thrown in continuous streams, the action is intermittent, the fountain throwing up successive sheets of matter instead of continuous streams." Newcomb and Holden, *Astronomy*, pp. 389–392.

swifter. Hence the comet's tail forms gradually, and grows longer and brighter to perihelion, and beyond, since the temperature of nucleus continues to increase for some time after the passage of the apsis. During the retreat toward aphelion, the tail dwindles to nothing again, often before the nebula itself has vanished out of sight.*

The general direction of the tail is always from the sun. But, on account of the comet's motion, the matter of the tail does not flow along the radius-vector produced, but in a direction inclined to this on the following side. The inclination varies with the variations of the comet's velocity and that of the atmosphere of the sun.†

Because the sun's atmosphere decreases in velocity outward, the comet's tail is curved so that the convexity precedes and the concavity follows, and the curvature increases from the nucleus to the outer extremity.‡

In its descent to perihelion the comet plunges through strata of the solar atmosphere that are successively denser and swifter, and, therefore, more powerful to blow the comet's atmosphere away. Hence the head of the comet continually diminishes to perihelion, and continually expands thereafter.§

* "When a comet first appears, in general, no tail is perceptible, and its light is very faint. As it approaches the sun it becomes brighter: the tail also after a time shoots out from the coma, and increases from day to day in extent and distinctness. As a comet recedes from the sun, the tail precedes the head, being still on the opposite side from the sun, and grows less and less at the same time that, along with the head, it decreases in brightness, till at length the comet resumes nearly its first appearance, and finally disappears."

"The tail of a comet is longest, and the whole comet is intrinsically the most luminous, not long after it has passed its perihelion." Norton's *Astronomy*, p. 203.

† "The general position of the tail of a comet is nearly but not exactly in the prolongation of the line of the centres of the sun and the head of the comet, or of the radius-vector of the comet. It deviates from this line on the side of the regions of space which the comet has just left; and the angle of derivation, which, when the comet is first seen at a distance from the sun, is very small or not at all perceptible, increases as the comet approaches the sun, and attains to its maximum value soon after the perihelion passage; after which it decreases, and, finally, at a distance from the sun, becomes insensible." Norton's *Astronomy*, 1845, p. 206.

This declination from the radius-vector is strong evidence that comets' tails are produced by an outflying atmosphere; for, were the tails produced by the action of such instantaneous agents as light, magnetism or electricity, emanating from the sun, there would be no initial declination, although there might be curvature.

‡ "Ordinarily the tail is not straight, but concave toward that part of the heavens which the comet has just left. This curvature of the tail is most observable near its extremity." Norton's *Astronomy*, p. 202.

§ "There is no doubt that many of these bodies contract as they approach the sun, and dilate on receding from that luminary." Hind's *Comets*, p. 19.

Often the energy of the solar stream becomes so great that the comet's vapors are blown back before they have condensed. Then the limpid stream rising toward the sun, meets the compacted solar atmosphere, is prevented from expanding, flows invisibly transverse, and, only when its backward journey is begun, reaches the region of condensation into mist.* Some comets have been completely stripped of vapors.†

As the comet's atmosphere is swept outward, it continues to expand. The rate of spreading of the tail is a function of the respective energies of the solar and cometary atmospheres.‡ The sweeping backward of the spheres of condensation creates, sometimes, the appearance of an even number of distinct tails;§ but the matter is continuous throughout the appendage, as it is in the head. The interior vapors, protected and confined, travel far as a limpid stream ere they can condense into visible mist, which finally they do, thus causing the far extremity of the tail to become uninterruptedly visible across its substance.‖

Free particles, projected by a comet's nucleus directly toward the sun, lose nothing of their moment of momentum with respect to the sun. Hence, the radius-vector of each particle describes area at the same rate as does the nucleus. If, therefore, these particles are pressed backward to the main orbit again by radial force, they will cross the orbit in advance

* See Newcomb and Holden, *Astronomy*, p 391.

† "There have been instances in which the comet seems to have been shorn of its hair; and, in one noteworthy instance, a comet of considerable splendor lost in a few days both its tail and hair." Proctor's *Orbs Around Us*, p. 224.

‡ "The tail of the comet is simply a continuation of the coma extending out to a great distance, and always directed from the sun. It has the appearance of a stream of milky light, which grows fainter and broader as it recedes from the head." Newcomb and Holden, *Astronomy*, p. 338.

§ "In some instances the nucleus is furnished with several envelopes concentric with it, which are formed in succession as the comet approaches the sun. For example, the comet of 1744, eight days after the perihelion passage, had three envelopes. Sometimes each of them is provided with a tail. Each of these several tails lying one within the other, being hollow, may in consequence appear so faint along its middle as to have the aspect of two distinct tails. A comet having in reality three separate tails, might thus appear to be supplied with six, as was the comet of 1744. If the different envelopes were not distinctly separate from each other, then we should have all the tails appearing to proceed from the same nebulous mass." Norton's *Astronomy*, p. 206.

‖ "The nucleus appears to possess the power of throwing off towards the sun a portion of the cometic atmosphere, which, before it can attain any great distance from the nucleus, is driven backward in two streams passing on either side of the head, and ultimately blending into one to form the tail." Hind's *Comets*, p. 25.

of the nucleus. For this reason, the stream of vapor that issues from the nucleus toward the sun, bends slightly forward from the radius-vector, and, consequently, the major portion of the returning current sweeps by the nucleus on its preceding side.*

The vapors swept away by the solar atmosphere are irrecoverably lost to the comet, which, therefore, continually wastes away.†

These are the main deductions from the theory, and also the main phenomena exhibited by comets.‡

The declination of the comet's tail from the radius-vector, and the velocity of the nucleus in its orbit, both determinable for any place by observation, make known the outflying velocity of the solar atmosphere at that same place. As these flaming torches are hurled through the solar atmosphere, at all altitudes, and in all directions, and upon every side of the sun, we may hope by their means to measure the velocity of that atmosphere in all its variations due to latitude and distance.

* "It has been generally found, also, that the tail appears brighter and better defined on the convex or preceding side, than it does on the opposite side." Grant's *History of Physical Astronomy*, 1852, p. 297.

† "'There is reason to believe that comets in general, for some unknown cause, decrease in splendor in each successive revolution.'" Quotation in Chambers' *Astronomy*, p. 399, from Smyth's *Cycle*, vol. i., p. 235.

‡ The complete theory of comets requires that the metamorphoses of the nuclei, and the connection between comets and meteor systems, be explained. A discussion of these two topics, already prepared, is appropriately omitted from the present essay.

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